THE RELIABILITY, VALIDITY AND TRAINABILITY OF RUNNING ECONOMY IN TRAINED DISTANCE RUNNERS

By

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ABSTRACT

Running economy is well established as a primary determinant of endurance running performance. However, there is a lack of clarity about the preferred measurement of running economy, its primary limiting factors and the most robust methods enhance running economy in highly trained athletes. Therefore, this thesis investigated the running economy of highly trained runners, exploring the reliability and validity of measures of running economy to deduce its most appropriate quantification, the application of innovative methods to enhance our understanding of an athlete's running economy, and a novel training method to enhance running economy. Chapter 3 revealed that energy cost and oxygen cost were shown to provide similarly high levels of reliability (typical error of measurement ~3%) for highly trained endurance runners when assessed using a short-duration incremental submaximal exercise protocol. In chapter 4, the analysis of a large cohort of highly trained endurance runners revealed that energy cost increased in a stepwise manner with increments in running speed ($P<0.001$), however oxygen cost remained consistent ($P=0.54$) across running speed; indicating that oxygen cost might not be an appropriate measure of running economy. Chapter 5 demonstrated that the inter-individual variation in the magnitude of changes in energy cost between different gradients (i.e. from flat running to uphill/downhill running) in highly trained runners was low. However, a disparity between the energy saving of running on a -5% gradient (-17%) and the additional energy cost of running on a +5% gradient (+32%) was evident. The cross-sectional and longitudinal analysis of a large cohort of highly trained runners in chapter 6 revealed a small ($r=0.25$) and moderate ($r=0.35$) association between energy cost and maximal oxygen uptake, respectively. Finally, chapter 7 demonstrated that eight weeks of supplementary downhill run training at vLTP in existing training programmes does not enhance running economy in already well trained runners (1.22 vs 1.20 $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$; $P=0.41$), despite a significant increase (+2.4%) in the velocity at lactate turnpoint. In conclusion, this thesis demonstrates that energy cost, expressed as $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$, provides a reliable and valid method to quantify running economy in trained distance runners. However, further investigation is required to identify robust training methods to enhance running economy in this already highly trained population.

Key words: Running economy, energy cost, oxygen cost, distance running, competitive athletes, training monitoring, gradient running, maximal oxygen uptake

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PREFACE

The work presented in this thesis has been peer reviewed as follows

Peer reviewed publications

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Chapter I

1.1 Introduction

The ability to travel a set distance in the shortest possible time via bipedal locomotion represents one of the most elemental, versatile and long standing forms of human competition. The time taken to complete the distance is often used to categorise events as sprint (5-90 s) or endurance events (>90 s); with the latter often broken down further for track and field athletes into middle- (800 m to 3,000m) or long (>3 km) distance races (Brandon 1995). The energy provided during endurance events is primarily from aerobic metabolism (Hill 1999; Duffield et al. 2005a), although for middle distance events, a substantial contribution from anaerobic metabolism is also evident (Duffield et al. 2005a). A number of deterministic physiological variables have been identified that are common across the spectrum of distance running events. The primary physiological determinants of endurance running performance are maximal oxygen uptake ($\dot{V}O_{2max}$), lactate threshold/fractional utilisation of $\dot{V}O_{2max}$ and running economy (Conley and Krahenbuhl 1980; Bassett and Howley 2000; Jones and Carter 2000; di Prampero 2003; Jones 2006; Joyner and Coyle 2008; Ingham et al. 2008) and the running velocity that can be sustained in any endurance event is largely dependent on the interaction of these variables.

Though a wealth of empirical investigations exist identifying the determinants of $\dot{V}O_{2max}$ and the fractional utilisation of $\dot{V}O_{2max}$, in addition to their responses to training, investigations exploring running economy are comparably limited (Foster and Lucia 2007). Running economy (RE) represents the metabolic cost of sustaining a given running speed (Daniels 1985; Larsen 2003; Joyner and Coyle 2008; Fletcher et al. 2009), thus reflecting the translation of energy turnover into linear running velocity. It has long been established that RE varies considerably between individuals (Daniels 1974; McMiken and Daniels 1976; Svedenhag and Sjödin 1994), with elite distance runners displaying superior RE compared to lesser trained individuals (Pollock 1977; Morgan and Bransford 1995). However, little focus to date has been directed towards some fundamental aspects of RE, such as the stability and validity of measures of RE, in addition to the primary determinants of RE.

Though some longitudinal interventions have explored the trainability of RE, the focus has been predominantly individuals with a low to moderate training status (e.g. Yoshida et al. 1990; Stray-Gundersen et al. 2001; Spurrs et al. 2003; Guglielmo et al. 2009; Berryman et al.

2010; Taipale et al. 2010), with a paucity of investigations in highly trained or elite populations. As improvements in $\dot{V}O_{2max}$ could be difficult to achieve in highly trained athletes (Lucía et al. 2002; Jones 2006; Iaia et al. 2009; Hopker et al. 2009), methods to enhance RE are sought after to maximise an athlete's performance. Though case studies have suggested that RE can be improved in elite populations (Jones 1998; Ingham et al. 2012), robust interventions to enhance RE in already highly trained individuals are limited (Lacour and Bourdin 2015; Barnes and Kilding 2015b). Therefore, the aim of the current thesis was to provide a comprehensive analysis of the RE of highly trained athletes; from the identification of the most reliable and valid measurement of RE, to potential factors that affect RE and interventions that could enhance this variable in this specific population.

Differing methods of quantifying RE are evident in the literature. Since its inception, measures of oxygen consumption, or oxygen cost (O_C), have formed the primary quantification of RE in experimental investigations (Conley and Krahenbuhl 1980; Williams and Cavanagh 1987a; Paavolainen et al. 1999; Saunders et al. 2004a), based on the assumption that $\dot{V}O_2$ provides an index of the underlying energy cost (E_C) when aerobic metabolism supplies virtually all of the energy requirements (Williams and Cavanagh 1987a; Fletcher et al. 2009). However, studies have also calculated the actual E_C from the O_C and the respiratory exchange ratio (Margaria et al. 1963; Folland et al. 2006; Fletcher et al. 2009). Though fundamental to any investigation exploring RE, empirical evidence detailing the reliability or validity of these different quantifications are rare. Therefore, chapter three examined the reliability of O_C and E_C measurements of RE in highly trained runners, and contrasted the reliability to the smallest worthwhile change for these measures. Chapter four assesses the validity of O_C as a measure of RE by comparisons to the underlying E_C, in addition to determining the most valid method of accounting for body mass in the measurements of RE. Findings from these studies were then used to inform the appropriate expression of RE in subsequent investigations.

Though many biomechanical and physiological variables are known to influence RE (Williams and Cavanagh 1987a; Barnes and Kilding 2015a; Lacour and Bourdin 2015), the primary limiting factors and their relative contributions is unclear (Joyner and Coyle 2008). As RE can be viewed as a composite of both mechanical and metabolic factors, diagnosis of specific mechanical or metabolic inefficiencies in an athlete could facilitate the prescription of more effective training interventions to enhance RE. The E_C of running on different surface gradients could potentially change the importance of metabolic and mechanical factors and provide useful diagnostic information. When running uphill, the body mass is lifted through each stride cycle (Snyder et al. 2012), with a lower vertical velocity on landing (Gottschall and Kram 2005; Neves, Johnson and Myrer 2014). The increased physiological work, with a reduced opportunity for elastic storage and utilisation (Snyder, Kram and Gottschall 2012) could result in E_C being more dependent on metabolic efficiency of an athlete. Conversely, when running downhill there is both a reduced requirement for positive work (Snyder, Kram and Gottschall 2012) and a higher vertical velocity on landing (Yokozawa et al. 2005; Gottschall and Kram 2005; Neves et al. 2014), providing a greater opportunity for elastic energy storage and re-utilisation. These differences between uphill and downhill running might shift the emphasis between metabolic and mechanical components of RE. Chapter five evaluates the E_C profiles of highly trained distance runners across these 3 gradients and assessed the variability in these responses, to potentially facilitate the identification of mechanical or metabolic inefficiencies.

Exceptional values of RE and $\dot{V}O_{2max}$ are considered requirements for success in elite endurance competitions. Consequently, highly trained runners strive to improve both variables through training in order to maximise performance. However, an inverse relationship has been reported between movement economy and $\dot{V}O_{2max}$ in both cross-sectional (Pate et al. 1992; Morgan and Daniels 1994) and longitudinal observations (Hopker et al. 2012); potentially indicating that enhancements in either RE or $\dot{V}O_{2max}$ might only be achievable at the expense of the other variable. However, previous investigations have been restricted to small sample sizes, with their results limited by the use of inappropriate statistical techniques that result in spurious correlations (Atkinson et al. 2003). Chapter six therefore explores the cross-sectional and longitudinal relationships between RE and $\dot{V}O_{2max}$ in a larger cohort of highly trained distance runners.

In the few studies with highly trained cohorts, findings suggest that short periods of supplementary exercises (e.g. high intensity interval training (Billat et al. 2002; Barnes et al. 2015)) or plyometric resistance training (Paavolainen et al. 1999; Saunders et al. 2006)) in addition to habitual training programmes could enhance RE. A lower E_C for a given speed (Margaria et al. 1963; Minetti et al. 2002) could increase the time spent at higher training velocities when running downhill, combined with the greater impact loads that occur during downhill running (Gottschall and Kram 2005; Yokozawa, Fujii and Michiyoshi 2005; Neves, Johnson and Myrer 2014). Consequently, downhill running could exaggerate stretch-shortening cycle activity, with the modality specificity potentially facilitating greater enhancements of RE. Chapter 7 therefore explores the efficacy of a supplementary 8-week programme of progressive downhill running as a means of enhancing RE in well-trained distance runners

Chapter II

Literature review

This chapter provides a critical review of the literature considering the physiological determinants of endurance running performance, with a specific focus on the RE of highly trained distance runners. Specific attention will be directed at the assessment of RE in trained athletes, the potential association between RE and $\dot{V}O_{2max}$, and training interventions to enhance RE in this already highly trained population. The final section of the review will explore the current methods used to monitor run training, with considerations of its application to elite distance runners.

2.1 The physiological determinants of endurance running performance

Aerobic metabolism forms the predominant energy source in all running events >400m (for athletes ~ 45-60s; Duffield et al. 2005a; Duffield et al. 2005b). For both middle and long distance running events, the sustainable performance velocity is principally determined by the interaction of an athlete's $\dot{V}O_{2max}$, the fractional utilisation of $\dot{V}O_{2max}$ and running economy (Conley and Krahenbuhl 1980; Bassett and Howley 2000; Jones and Carter 2000; di Prampero 2003; Joyner and Coyle 2008; Figure 2.1).

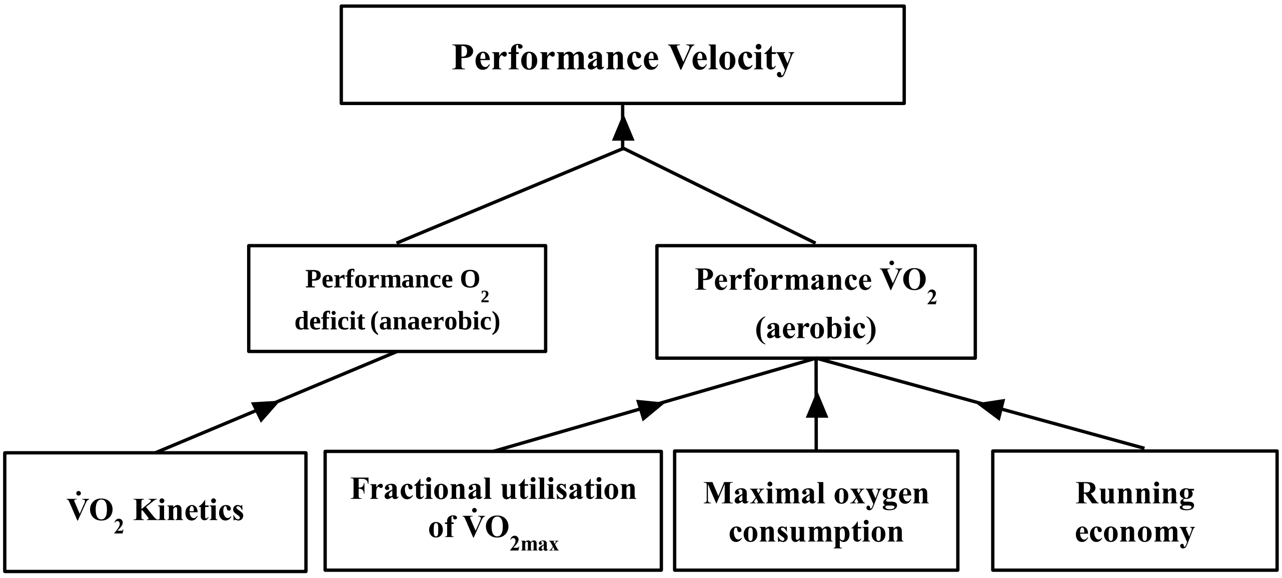

Figure 2.1. A schematic representation of the physiological factors that interact to determine performance velocity in endurance running events. Adapted from Joyner and Coyle (2008) and Jones (2006).

2.2 Maximal oxygen uptake ($\dot{V}O_{2max}$)

Maximal oxygen uptake is defined as the highest rate at which oxygen can be utilised by the body during whole body exercise (Bassett and Howley 2000). It has long been established that $\dot{V}O_{2max}$ is significantly greater in high-level endurance athletes, with typical values between 65-85 $ml.kg^{-1}.min^{-1}$ often reported for trained endurance runners (Svedenhag and Sjödin 1985; Zhou et al. 2001; Ingham et al. 2008) compared to <60 $ml.kg^{-1}.min^{-1}$ for recreationally active (Ramsbottom et al. 1987) or <40 $ml.kg^{-1}.min^{-1}$ for untrained individuals (Moore et al. 2012). Thus, in a heterogeneous population, $\dot{V}O_{2max}$ has been identified as a good predictor of endurance performance (Costill 1967; Foster et al. 1978), and as such a high $\dot{V}O_{2max}$ is seen as a prerequisite for elite endurance performance (Jones 2006). The $\dot{V}O_{2max}$ of an athlete is commonly assessed via incremental exercise protocols to volitional exhaustion with concurrent assessments of gaseous exchange, quantified as the rate of oxygen uptake ($\dot{V}O_2$) during the final 30-60s of exercise (Ramsbottom et al. 1987; Svedenhag and Sjödin 1994), or the greatest 15-30s average $\dot{V}O_2$ response where breath-by-breath analysis is available (Billat et al. 1999; Ingham et al. 2008; Ferri et al. 2012).

Oxygen utilisation during maximal exercise is determined by both the delivery and subsequent extraction/utilisation of oxygen by the active skeletal musculature. Though much debate still exists (Spurway et al. 2012), it is generally accepted that cardiovascular factors such as cardiac output (Blomqvist and Saltin 1983; Andersen and Saltin 1985), haemoglobin mass (Schmidt and Prommer 2008) and capillary density (Andersen and Henriksson 1977) are the primary factors that limit an athlete's $\dot{V}O_{2max}$. However, a capacity to utilise the additional flux of O_2 in the activate musculature must also be evident. Consequently, peripheral intra-muscular properties such as mitochondrial density and enzyme activity also exert a direct influence on the $\dot{V}O_{2max}$ of an individual (Holloszy and Coyle 1984).

2.3 Fractional utilisation of $\dot{V}O_{2max}$ and blood lactate thresholds

The proportion of $\dot{V}O_{2max}$ that can be sustained over a given race distance has also been identified as a deterministic factor of endurance performance (Costill et al. 1973; Maughan and Leiper 1983; Svedenhag and Sjödin 1985). Strong correlations have been reported between fractional utilisation of $\dot{V}O_{2max}$ and running performances over various race distances, including 5 km (Sjodin and Schele 1982) and 16.1 km (Costill et al. 1973), accounting for 88% of the variation in performance over both distances. This variable has been closely associated with markers of blood lactate accumulation, most notably lactate threshold and lactate turnpoint (Costill et al. 1973; Sjödin and Svedenhag 1985; Jones and Carter 2000).

It is well established that a curvilinear relationship exists between blood lactate accumulation and increments in exercise intensity (Figure 2.2). Elevations in blood lactate are seen to arise when Nicotinamide adenine dinucleotide (NADH) and hydrogen ions (H^+) from cytosolic reactions are produced at rates in excess of mitochondrial capacity (Robergs et al. 2004). Although no longer directly implicated in the effects of muscle fatigue itself, blood lactate concentration ($[La]_b$) is known to be a surrogate indicator for increased H^+ release and a subsequent lowering of cellular and blood pH (Robergs et al. 2004). It is this accumulation of H+, in addition to increases in inorganic phosphate (Westerblad et al. 2002) that is likely to contribute to the muscle fatigue experienced during intense periods of exercise.

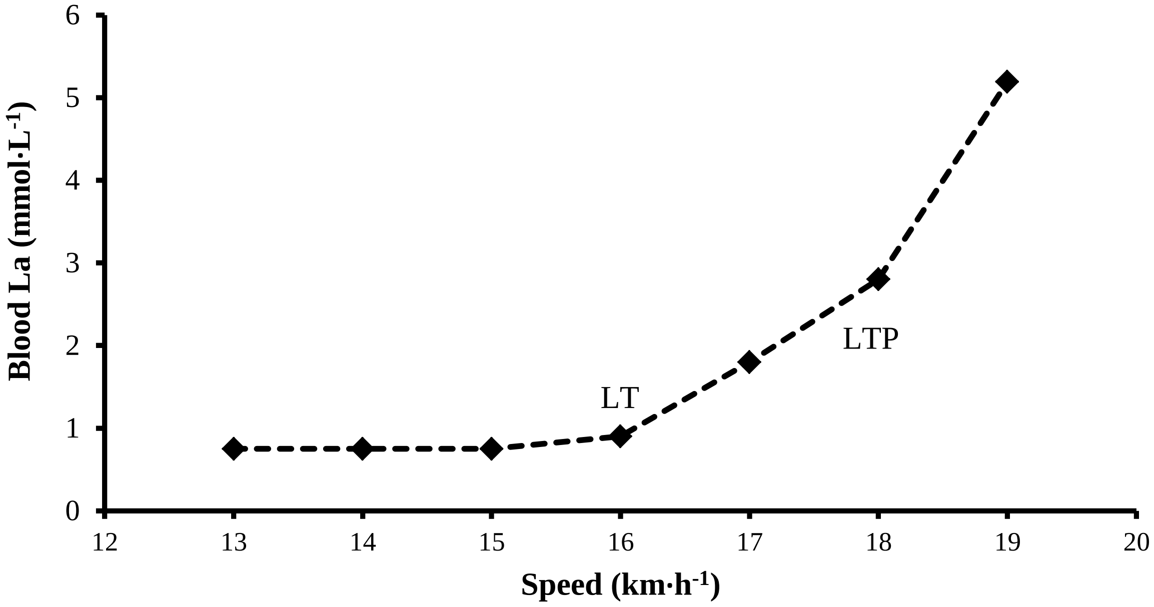

Figure 2.2. A typical blood lactate concentration vs speed relationship assessed by a 7 x 3 minute stage incremental running test for a well-trained middle distance runner. LT demarcates lactate threshold, LTP demarcates lactate turnpoint.

Lactate thresholds are commonly identified through short stage, incremental exercise tests with concurrent assessments of $[La]_b$ (Jones 2006; Ingham et al. 2008; Ingham et al. 2012). During exercise of a low intensity, $[La]_b$ remains close to resting values (~1.0 mmol.l^{-1}). As exercise intensity progresses, $[La]_b$ increases above baseline, defined as the lactate threshold (LT). Despite this rise in $[La]_b$, a steady state environment is still maintained if exercise intensity is stable, reflecting a balance between the rate of lactate production in the muscles and subsequent cellular clearance. If intensity continues to increase beyond LT, a second 'sudden and sustained' breakpoint in [La]b can be identified (Jones 2006). This threshold intensity, referred to previously as the maximal lactate steady state (Smith and Jones 2001) and onset of blood lactate accumulation (Sjödin and Jacobs 1981), represents the lactate turnpoint (LTP). In response to work beyond this threshold intensity, $[La]_b$ increases inexorably until exercise is terminated (Jones 2006).

For untrained cohorts, LT typically occurs at exercise intensities eliciting 50-70% $\dot{V}O_{2max}$ (Jones 2006; Joyner and Coyle 2008). However, LT at relative intensities as high as 80-85% have been reported for elite middle distance runners (Ingham et al. 2008) and highly-trained marathon and ultra-marathon runners (Sjödin and Svedenhag 1985). Periods of endurance training are known to decrease lactate production and increase clearance at a given relative exercise intensity (Hurley and Hagberg 1984), resulting in LT and LTP occurring at a higher fraction of $\dot{V}O_{2max}$. Such ability to undertake high intensity exercise without creating large disturbances in muscle homeostasis is believed to be primarily a result of enhanced oxidative capacity, in addition to enhanced lactate transportation/buffering, within the skeletal muscle of elite endurance athletes (Hawley 2002). Strong positive relationships have previously been identified between the proportion of type I muscle fibres, a fibre type with intrinsically high mitochondrial content and capillary density (Costill 1967; Saltin et al. 1977), and the relative intensity at which LTP occurs in moderately trained individuals (Ivy et al. 1980; Tesch et al. 1981). Moreover, mitochondrial density and the content/activity of mitochondrial enzymes, such as succinate dehydrogenase (SDH), in addition to muscle capillarity, are also known to determine the fractional utilisation of $\dot{V}O_{2max}$ (Sjödin and Jacobs 1981; Holloszy and Coyle 1984).

2.4 **Oxygen uptake kinetics**

The rate at which $\dot{V}O_2$ rises at the onset of exercise, defined as the $\dot{V}O_2$ kinetics, has been consistently associated with performance in endurance running events (Jones and Carter 2000; Burnley and Jones 2007), with cross sectional analyses revealing faster attainment of requisite steady state $\dot{V}O_2$ in trained endurance athletes compared to untrained controls (Koppo et al. 2004; Ingham et al. 2007). Assessed via breath-by-breath analysis, the $\dot{V}O_2$ kinetics from the onset of moderate intensity exercise can be categorised into 3 distinct phases. Phase I, referred to as the "cardio-dynamic" phase, reflects the abrupt increase in $\dot{V}O_2$

at the onset of exercise, predominantly mediated by an increased venous return and increased ventricular output (Burnley and Jones 2007). Phase II, defined as the primary or fast component, reflects the kinetics of the muscle $\dot{V}O_2$ (Grassi and Poole 1996), with phase III reflecting the steady state of $\dot{V}O_2$ (Burnley and Jones 2007). For exercise intensities above the LT, the phase III $\dot{V}O_2$ shows a progressive increase to a $\dot{V}O_2$ greater than the expected from the sub LT $\dot{V}O_2$ vs running speed relationship with a considerably slower time course than phase II, referred to as the slow component (Jones et al. 1999; Burnley and Jones 2007). Though the slow component will stabilise at intensities below LTP, beyond LTP $\dot{V}O_2$ will continue to rise towards its maximum value with time, with fatigue following shortly after (Burnley and Jones 2007).

It is now well accepted that the magnitude of the initial oxygen deficit at the onset of exercise is regulated by the speed $\dot{V}O_2$ kinetic responses (Jones and Carter 2000). Faster $\dot{V}O_2$ kinetics leads to a quicker attainment of the required steady state $\dot{V}O_2$, and consequently can facilitate a reduction in metabolic perturbations and blunt the rate of fatigue development (Burnley et al. 2000; Rossiter et al. 2001; DiMenna et al. 2010). Moreover, faster $\dot{V}O_2$ kinetics can lead to an increase in the energy contribution from aerobic metabolism during high intensity running bouts (Ingham et al. 2013). As non-oxidative energy provisions are finite (Ferguson et al. 2007; Burnley and Jones 2007), the increase in oxidative energy contributions could attenuate depletion of anaerobic provisions and thus enhance performance, particularly in middle distance events where greater anaerobic contributions to overall energy turnover are seen when compared to long distance events (Gastin 2001). Though much debate surrounds the principle limiting factor (Poole et al. 2008), evidence suggests the O_2 kinetic responses of an athlete are regulated by both $\dot{V}O_2$ delivery and the inertia of the intracellular oxidative machinery (Grassi et al. 1996; Poole et al. 2008).

2.5 **Running economy**

RE represents the translation of aerobic energy turnover into linear running velocity, and forms a critical determinant of endurance running performance (Conley and Krahenbuhl 1980; Bassett and Howley 2000; Jones and Carter 2000; di Prampero 2003; Jones 2006; Joyner and Coyle 2008; Ingham et al. 2008). In homogenous populations of highly trained runners, RE has been shown to account for 65% of the variation in race performance over 10km (Conley and Krahenbuhl 1980). Moreover, the combination of RE and $\dot{V}O_{2max}$ has been shown to explain 96% of the variance in the performance of national and international middle distance runners (Ingham et al. 2008). Regardless of its expression, the lower the metabolic cost assessed at a given speed of running, the better the RE of an individual (Figure 2.3).

It has long been established that RE varies considerably between individuals (Daniels 1974; McMiken and Daniels 1976; Svedenhag and Sjödin 1994). Observations of athletic populations highlighted superior RE for elite distance runners compared to good distance runners and untrained individuals (Pollock 1977; Morgan and Bransford 1995). When quantified as the O_C per kilo of body mass over a given horizontal distance (mL.kg^{-1}.km^{-1}), a value of 200 is considered an average RE (Jones 2006). For elite endurance runners, values of 180-195 mL.kg^{-1}.km^{-1} are commonly observed (Pollock 1977; Brisswalter and Legros 1994a; Saltin et al. 1995; Jones 2002; Tam et al. 2012), with figures as low as 150-165 mL.kg^{-1}.km^{-1} having been reported in exceptional cases (Jones 2006; Lucia et al. 2008). Moreover, when categorised by competitive distances, a superior RE has been reported in long distance runners when compared to middle distance runners (191 mL·kg^{-1}·km^{-1} vs 196 mL·kg^{-1}·km^{-1}, respectively; Svedenhag and Sjödin 1994). The differences in RE observed between individuals is attributed to the weighted sum of the influences from many anthropometrical,

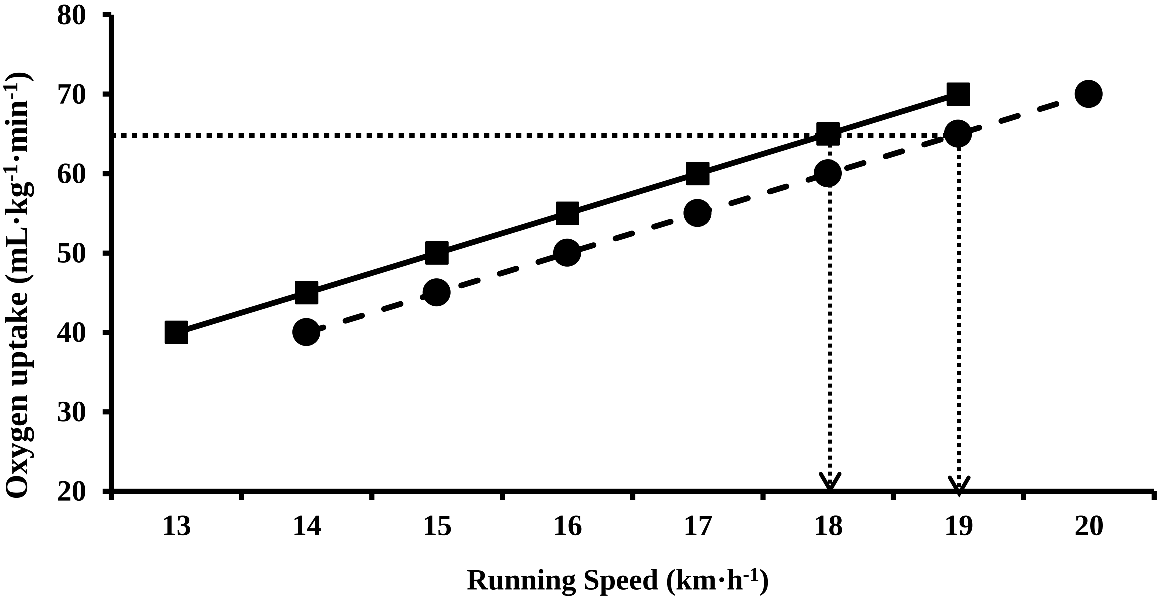

Figure 2.3. A graphical representation of the $\dot{V}O_2$ response in a submaximal running assessment for two athletes with the same $\dot{V}O_{2max}$ and fractional utilisation of $\dot{V}O_{2max}$, but differing running economies. For a given $\dot{V}O_2$ (i.e. 65 mL·kg^{-1}·min^{-1}), the athlete with superior running economy (black circles) can achieve a running speed 1km·h^{-1} greater than the athlete with inferior running economy (black squares). Adapted from Jones (2006).

biomechanical and physiological variables (Figure 2.4), that will be discussed. However, the primary determinant of RE remains unclear (Joyner and Coyle 2008).

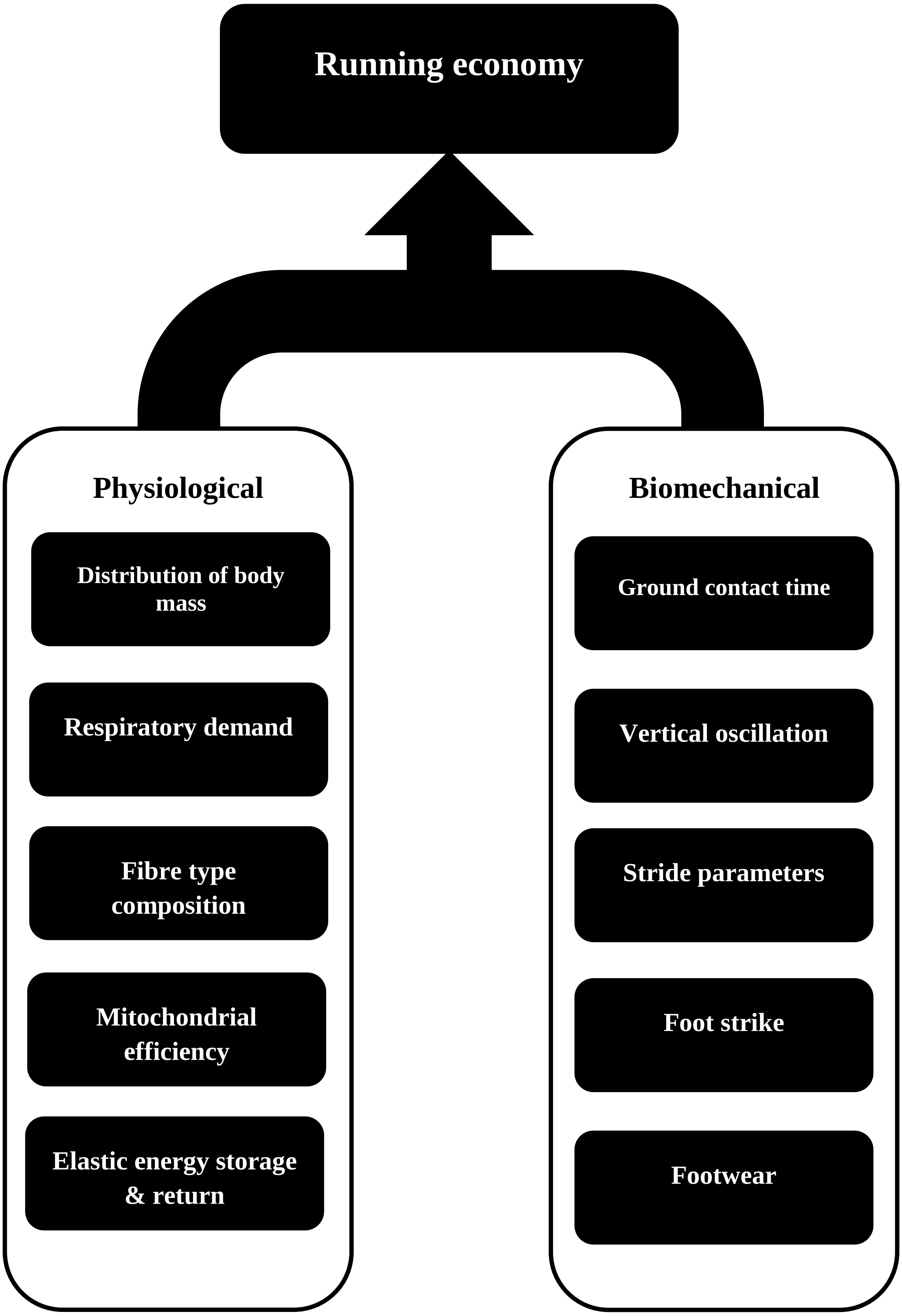

Figure 2.4. Key physiological and biomechanical factors affecting running economy.

2.5.1 **Measurement of running economy**

Although often overlooked, the methods and procedures employed to measure RE are pivotal to any assessment of this variable. Though all measures of RE are based on a common principle (i.e. the translation of energy turnover into running velocity), multiple quantifications of RE are evident in the literature. Moreover, the protocols and methods used to assess RE can vary considerably between investigations. It is therefore critical to first consider the validity and reliability of RE assessment.

2.5.1.1 Quantifications of running economy

At its most basic level, the validity of a variable can be viewed as the extent to which the data measured represents what it is intended to measure (Newman and Benz 1998). When applied to RE, a valid assessment would be the direct assessment or an accurate proxy of the underlying metabolic cost of running. In the absence of direct measures, assessments of pulmonary gas exchange have been used to quantify RE. In principle RE encompasses both aerobic and anaerobic energy turnover, however the restricted ability to accurately assess anaerobic metabolism limits measure of RE to quantifications of aerobic metabolism. Though originally assessed by Douglas bag methods, technological developments have led to the use of metabolic measuring systems that provide a breath-by-breath analysis during exercise bouts (Figure 2.5). Validation studies comparing measures of gaseous exchange and ventilation from Douglas bags, the gold standard, and online metabolic measurement systems (i.e. the ‘Oxycon-pro) have demonstrated their accuracy during both low intensity and maximal exercise (Ritjens et al. 2001).

For several decades, measures of oxygen consumption have formed the primary quantification of RE in experimental investigations (Conley and Krahenbuhl 1980; Williams and Cavanagh 1987a; Paavolainen et al. 1999; Saunders et al. 2004a), based on the assumption that oxygen cost (O_C) provides an index of the underlying energy cost (E_C) when aerobic metabolism supplies virtually all of the energy requirements (Williams and Cavanagh 1987a; Fletcher et al. 2009); leading to some authors to using the terms O_C and E_C interchangeably (Bourdin and Pastene 1993; Brisswalter and Legros 1994b; Maldonado et al. 2002). Despite this assumption, investigations comparing the response of both O_C and the actual E_C during submaximal exercise are limited. However, recent evidence suggests a discrepancy may exist between the response of E_C and O_C with increments in running speed (Fletcher et al. 2009), bringing into question the validity of O_C to quantify RE.

Figure 2.5. The assessment of gaseous exchange by an online metabolic measurement system during a treadmill based running test in the laboratory

Previous investigations have consistently cited that O_C is independent of running speed, thus remaining uniform with increments or decrements in exercise intensity between 55-80% $\dot{V}O_{2max}$ (Margaria et al. 1963; Hagberg and Coyle 1984; di Prampero et al. 2009; Fletcher et al. 2009). Intuitively, as O_C is used as a surrogate marker of E_C at submaximal intensities, both O_C and E_C would be expected to display a similar relationship with running speed. However, E_C has been shown to be positively related to speed; increasing with increments in relative running towards vLTP (Fletcher et al. 2009). This clear disparity between the relationship of O_C and E_C with running speed is likely driven by the confounding influence that variations in substrate utilisation have on O_C.

It is well established that differences exist in the O_C of metabolising carbohydrates and lipids, with a greater energy equivalent of O_2 for carbohydrate (5.02 kcal·L^{-1}) compared to lipid (4.85 kcal·L^{-1}) metabolism (Krogh and Lindhard 1920; Jeukendrup and Wallis 2005).

Consequently, the global O_C to maintain a given energy demand is heavily dependent on the relative contribution of these substrates during submaximal exercise bouts (Jequier et al. 1987). Whilst direct measurement is invasive, the relative contributions of these substrates to energy turnover can be estimated based on the respiratory exchange ratio (RER) (Krogh and Lindhard 1920). Previous investigations have consistently highlighted a positive association between the RER and submaximal exercise intensity, reflecting a shift towards greater carbohydrate metabolism and less fat metabolism at higher exercise intensities (Saunders et al. 2004a; Fletcher et al. 2009). It is therefore plausible that, despite elevations in the E_C as exercise intensity increases, the alteration in substrate metabolism towards a more oxygen efficient substrate may offset the expected increase in O_C. Since the use of RER is inherent to the calculation of actual E_C via pulmonary gas measures, E_C is not influenced by any alterations in substrate metabolism during exercise, thus enabling the identification of the true relationship of RE and relative running speed. Whilst these findings do not discount the clear and well established importance of O_C to endurance running performance, as O_C represents a composite of both energy turnover and substrate utilisation, E_C would appear to provide a more appropriate expression of running economy. However, evidence to support this hypothesis has been limited to one investigation using a small cohort of runners (Fletcher et al. 2009), thus further study is warranted to substantiate these findings.

During each running stride, work is required to transfer the total mass of the body from one leg to the other, interspersed by a period of flight. Consequently, the metabolic cost incurred is directly influenced by the body mass of the individual. Therefore, to enable accurate and useful inter- and intra- individual comparisons of RE, measurements of RE must be independent of body mass. Previous investigations have often expressed RE as a ratio of BM, e.g. $RE.BM^{-1}$ known as ratio scaling (Margaria et al. 1963; Pate et al. 1992; Bourdin and Pastene 1993; Prampero et al. 1993; Morgan and Daniels 1994; Saunders et al. 2004c; Fletcher et al. 2009; Tam et al. 2012) under the assumption that a proportional linear relationship exists between these two variables. However, empirical evidence to support this assumption is sparse. Moreover, expressed relative to BM^{-1}, previous investigations have reported an inverse relationship to exist between BM and O_C (Pate et al. 1992; Bourdin and Pastene 1993), which could indicate that the ratio scaling of RE overcompensates for BM (Tanner 1949). Studies of heterogeneous cohorts with athletes from various sport disciplines have suggested that scaling exponent less than one should be used, specifically $BM.^{-0.75}$

(Bergh et al. 1991). However, these findings have yet to be substantiated in a large cohort of endurance runners. Moreover, previous investigations exploring the relationship of BM with RE have solely employed O_C to quantify this variable. It is therefore of great interest whether E_C should be raised to the same exponent as O_C to account for differences in BM.

2.5.1.2 The running speed / intensity of RE measurements

Although ideally assessed directly, practical and technological constraints result in the use of pulmonary gaseous exchange to provide indirect assessments of RE for individuals. Moreover, despite the RE at race pace forming the primary point of interest, assessments of economy are restricted to submaximal running speeds that are often markedly lower velocities. This is primarily due to the aforementioned appearance of a $\dot{V}O_2$ slow component that does not stabilise beyond this LTP, in addition to an increase in anaerobic contributions to energy turnover. Consequently, beyond LTP, the measurement of $\dot{V}O_2$ cannot account for the entire rate of energy turnover (Svedahl and MacIntosh 2003). Moreover, the increased glycolytic flux beyond LTP leads to an accumulation of H^+, liberating non-oxidative CO_2 from the bicarbonate pool that would create an excessive $\dot{V}CO_2$ (Romijn et al. 1992). Consequently, estimations of energy turnover beyond LTP via gaseous exchange would be flawed (Jeukendrup and Wallis 2005). Therefore, methods to assess RE must be below LTP to circumvent the aforementioned limitations. Given the intensity of 10km run performance (85-95% $\dot{V}O_{2max}$; Weston et al. 2000; Billat et al. 2003) is likely to be close to, if not in excess of LTP, valid assessments of RE for race distances of ≤5km are not possible through indirect calorimetry.

Despite the limitations of RE assessments beyond LTP, previous investigations have employed standardised running speeds, or standardised intensities expressed relative to $\dot{V}O_{2max}$. Given that substantial variation can occur in the percentage $\dot{V}O_{2max}$ at which LTP can occur even in homogenous cohorts (Coyle and Coggan 1988), the methods standardising exercise intensity to $\dot{V}O_{2max}$ are likely to result in the $\dot{V}O_2$ slow component being evident in some participants, but not others, thus compromising the validity of comparisons (Whipp 1994). Running speeds standardised to the velocity of vLTP would therefore appear to be the most appropriate method to overcome this issue, and facilitate accurate intra- and inter-individual comparisons (Fletcher et al. 2009).

A fundamental assumption of indirect calorimetry via gaseous exchange is that respiratory exchange ratio (RER) adequately mirrors the respiratory quotient (RQ), where pulmonary assessments of $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$) reflect oxidative metabolism; thus providing an index of gas exchange from fuel metabolism at the tissue level (Romijn et al. 1992). The increased acidosis associated with velocities beyond LTP would disturb the stability of the bicarbonate pool, increasing $\dot{V}CO_2$. Moreover, the LTP also demarcates the velocity beyond which significant anaerobic contributions to energy turn over are apparent (Billat et al. 2003). Given the incomplete oxidation of energy substrates that is associated with anaerobic metabolism, further disparity between the RER and RQ would arise. Therefore, at exercise intensities beyond LTP, estimations of energy turnover via indirect calorimetry are flawed (Jeukendrup and Wallis 2005). Consequently, exercise intensities at a given percentage of the velocity at LTP (vLTP) would appear the most appropriate to enable valid inter-individual comparisons of RE. However, it should be noted that absolute speed is unlikely to not be uniform across cohorts when relative intensities to vLTP are employed, with higher running speeds resulting in a greater energy requirement. To circumvent this limitation, quantifications of RE should be expressed as a ‘cost’ to cover a given distance ($\cdot km^{-1}$), rather than a rate ($\cdot min^{-1}$).

2.5.1.3 Over ground vs treadmill assessments

Though the vast majority of endurance running races occur outdoors, assessments of RE are typically made within a laboratory on motorised treadmills. Consequently, concerns have arisen regarding differences between treadmill and over ground assessments of RE (Daniels 1985). The effect of headwinds and air resistance are seen to have a substantial influences on RE, with previous investigations highlighting that ~8% of the energy cost incurred during 5000m running can be attributed to overcoming air resistance (Pugh 1970), which logically increase with increments in running velocity (Daniels 1985). As little air resistance is encountered during treadmill running, it would be expected that assessments of RE made under these conditions may underestimate the true RE of over ground running. Indeed, a 15% greater $\dot{V}O_2$ was apparent when participants were exposed to headwinds experienced in over ground conditions during treadmill running when compared to control conditions (Costill and Fox 1969). Though it may appear that outdoor assessments may provide a more valid measurement, it must be noted that the reliability of a measure is inherent to its validity (Newman and Benz 1998). Given the environmental conditions are highly variable outdoors, the inability to standardise the conditions during over ground running is likely to compromise the reliability of measures; reducing the validity. However, is has been shown that treadmill belts inclined at 1% can accurately mimic the energetic cost of outdoor running in well trained, treadmill habituated athletes, at speeds of 10.5 - 18 km·h^{-1} (Jones and Doust 1996). Moreover, similar kinematic and kinetic charactertics are seen between treadmill and over ground running (Riley et al. 2008). As laboratory conditions can be controlled and easily replicated, it is likely that treadmill running can provide the most reliable, and thus valid, assessment of RE.

When interpreting assessments of RE from treadmill running, consideration must be made for the influence of surface compliance of the belt. Typically, research grade treadmills have rigid decks, creating a comparable vertical stiffness to that experienced during road running (Tung et al. 2013). However, empirical investigations are not limited to this type of treadmill, thus variations are evident with regards to belt compliance and surface stiffness. Surfaces that facilitate elastic rebound are known to improve RE, contributing a greater proportion of work that would otherwise be provided by the runner (Kerdok et al. 2002). Conversely, excessive dampening properties of the running surface have been shown to increase the metabolic cost of running (Hardin et al. 2004). Therefore, caution should be exercised when inter-investigation comparisons are made, particularly when rigid decked treadmills are not employed. Moreover, the use of the same treadmill for repeated assessments is imperative to accurate assessments of changes in RE over time.

2.5.1.4 The reliability of running economy

Prior to the exploration of appropriate interventions to enhance RE, knowledge of the between-test reliability is required. The between-test reliability reflects the stability and repeatability of a measure (Newman and Benz 1998), providing an estimate of the accuracy to which changes in the given variable can be detected. This measure of reliability relates to the random error, or ‘noise’, that occurs between assessments despite identical protocols and conditions being upheld. The primary factors contributing to between-test variability can be categorised as biological error (i.e. unexpected changes in physiological or psychological responses) and/or technical/equipment error (Batterham and George 2003). Reductions in the noise from either component will therefore enhance the reliability of a measure.

Using submaximal treadmill assessments, relatively high levels of between test reliability in RE have been observed, reflected by low coefficients of variation (1-5%) for populations of varying athletic ability (Table 2.1). In attempts to reduce the biological error between measurements, studies have employed various experimental controls, including restrictions on the training and nutrition prior to assessments (Morgan et al. 1991; Brisswalter and Legros 1994b; Pereira and Freedson 1997). Though such controls clearly enhance the between-test reliability (Table 2.1), it must be noted that these experimental controls (i.e. standardising diet, training and time of day etc) are frequently impractical for the monitoring of athletes in full time training. Methods to enhance the between-test reliability without imposing additional constraints on the athlete’s day-to-day lifestyle are therefore desirable.

All previous investigations exploring the reliability of RE have employed O_C as the quantification of RE (Table 2.1). As outlined previously, this measure is susceptible to changes in substrate metabolism that may result from an altered diet or training bouts prior to RE assessments. Quantification of RE as E_C might mitigate the confounding influence of substrate utilisation on O_C, providing greater reliability without prior dietary and training restrictions. Moreover, as the $\dot{V}CO_2$ measurement needed to calculate RER is routinely assessed simultaneously to $\dot{V}O_2$, no additional constraints are imposed on participants. However, whether E_C provides a more reliable assessment of RE than O_C remains to be elucidated.

2.5.1.5 Limitations of running economy assessments

The assessment of RE via pulmonary gaseous exchange provides a global assessment of the metabolic cost within the body at a given time. As a result, it is not possible to discriminate the relative proportion of energy turnover from various components within the body, such as demand from cardiac activity, ventilatory activity, or specific proportions of active skeletal muscle. Therefore, the ability to identify the primary limiting factor of RE in an individual might be limited by the use of indirect calorimetric.

2.5.2 **Factors affecting running economy**

2.5.2.1 Physiological factors

Anthropometry

Various anthropometrical characteristics have been proposed to affect the biomechanical effectiveness with which muscular activity is translated into locomotion (Anderson 1996). Although general body mass is often accounted for and thus does not influence RE per se, the distribution of mass across the body could play an important role in determining the metabolic cost of locomotion. It is known that mass carried distally on limbs increases the energy requirement during running to a greater extent to that carried closer to the centre of mass, with previous findings showing an increase in $\dot{V}O_2$ by 1% when an additional 1kg load is carried on the trunk of an athlete, compared to a 7-10% increase in $\dot{V}O_2$ when an equal load is carried on the foot (Myers and Steudel 1985; Martin 1985). In addition, more distally distributed mass on the lower limbs might require more kinetic energy to overcome the moment of inertia and accelerate and decelerate limbs, evidenced by a smaller 3.5% increase in $\dot{V}O_2$ when an equal 1kg load was carried on the thigh (Myers and Steudel 1985). Elite endurance runners often possess characteristics such as slender body types and slim limbs (Saltin et al. 1995; Lucia et al. 2006; Fudge et al. 2006; Kong and Heer 2008). In addition, smaller calf girths have been observed in elite long distance runners (Lucia et al. 2006; Kong and Heer 2008; Lucia et al. 2008) when compared to the average of athletically heterogeneous cohorts (Pate et al. 1992).

Moreover, observations of relatively lower calf girths for adolescent Kenyan males to that of Caucasian counterparts has led to the speculation that smaller limb dimensions, and thus mass, is an important contributory factor to the superior RE of Kenyan runners (Larsen 2003; Foster and Lucia 2007).

Respiratory properties

Previous investigations have noted an association between the cardio-respiratory demands during submaximal running and RE (Pate et al. 1992; Thomas et al. 1995; Franch et al. 1998) .In an early study, the indirect measures of oxygen costs from the mechanical work estimated the oxygen demand of ventilation to be ~6% of the total $\dot{V}O_2$ during exercise (Milic-Emili et al. 1962). A subsequent cross-sectional investigation of trained runners demonstrated small association (r=0.4) between minute ventilation and O_C at 16.1 $km \cdot h^{-1}$ (Pater et al. 1992). Furthermore, strong positive associations have been noted between minute ventilation and changes in O_C during extended periods of exercise (Thomas et al. 1995) and following intensified training (Franch et al. 1998).

Table 2.1. Summary of findings for between test reliability of O_C measurements obtained via submaximal treadmill running assessments.

Authors	**Population** Athletic status (*n*)	**Protocol** No. of assessments (time period in days) and speed	**Experimental controls**				**Between test variation** CV
			Time of day	Footwear	Diet	Training	
Williams et al. 1991	Moderately trained males (10)	20 (28) at 9.6, 11.3 and 12.9 $km.h^{-1}$	✓	✓	✓	✓	2.72%
Morgan et al. 1991	Moderately trained males (17)	2 (2) at 12 $km.h^{-1}$	✓	✓		✓	1.32%
Brisswater and Legros 1994	Elite males (10)	4 (7) at 75% $_{V}\dot{V}O_{2max}$	✓	✓		✓	4.65%
Pereira et al. 1994	Moderately trained males (5)	10 (35) at 70% $_{V}\dot{V}O_{2max}$	✓	✓	✓	✓	1.47%
Pereira and Freedson 1997*	Highly trained males (7)	3 (21) at 75% $_{V}\dot{V}O_{2max}$	✓	✓	✓	✓	1.77%
Pereira and Freedson 1997*	Moderately trained males (8)	3 (21) at 75% $_{V}\dot{V}O_{2max}$	✓	✓	✓	✓	2.00%
Saunders et al. 2004	elite males (11)	2 (7) at 14, 16 and 18 $km.h^{-1}$	✓	✓			2.70%

*- denotes data from the same investigation. CV – Coefficient of variation; $_{V}\dot{V}O_{2max}$ – velocity associated with maximal oxygen uptake

Muscle-tendon properties

Skeletal muscle fibre type composition

Skeletal muscle fibres are often categorised as slow twitch (type I) or fast twitch (type II), based on their enzymatic and contractile properties (Essén et al. 1975; Billetter. et al. 1980). Type I fibres display characteristics that are tailored towards aerobic metabolism (Essen et al. 1975), with a maximal shortening velocity 3-5 times slower than Type II fibres (Fitts et al. 1989). Previous evidence has suggested a comparative efficiency of type I over type II muscle fibres for a given force generation (Wendt and Gibbs 1974; Katz et al. 1986; Hunter et al. 2001). Moreover, as both type I and II fibres display the highest efficiency at ~1/3 of the maximal shortening velocity, it is logical that type I fibres could display greater efficiency at the relatively slow shortening velocities associated with submaximal exercise (Coyle et al. 1991). It has long been established that the trained musculature of elite endurance runners contains a high proportion of type I muscle fibres (Costill et al. 1976). Inter-individual variations of exercise economy in endurance athletes have been largely attributed to type I fibre content within skeletal musculature in cycling (Coyle et al. 1991). Greater proportions of type I fibres have also shown moderate associations with enhanced RE at relatively low (11-13 km·h^{-1}) running speeds (Bosco et al. 1987; Kaneko 1990). Conversely, in a study of highly trained runners, no association has been reported between type I fibres and RE at submaximal running speeds between 14.5 and 20 km·h^{-1} (Kyrolainen et al. 2003). However, a large inverse relationship (r = -0.68) has been reported between walking economy and type II muscle fibre (Hunter et al. 2001). It has been postulated that the lack of a clear association between economy and fibre type in running might reflect the more complex locomotive pattern to that of cycling (Joyner and Coyle 2008).

Mitochondrial efficiency

The amount of oxygen consumed to phosphorylate adenosine diphosphate (ADP) to form ATP, referred to as the P/O ratio, represents the efficiency of mitochondrial oxidative phosphorylation (Hinkle 2005). Within mitochondria, the oxidation of substrates liberates protons to enter the electron transport chain; resulting in a transmembrane proton gradient that is the basis for ATP resynthesis. However, other factors are known to dissipate the transmembrane potential other than phosphorylation, thus proton liberation does not match ATP production, termed ‘uncoupling’ (Larsen et al. 2011). Logically, increasing the P/O ratio could lead to an enhancement in RE. Indeed, dietary supplementation of nitrates have been shown to acutely increase the P/O ratio (Larsen et al. 2011), potentially mediating a reduced O_C in submaximal exercise (~4-6%) following nitrate supplementation (Larsen et al. 2007; Bailey et al. 2009; Lansley et al. 2011). However, investigations exploring the influence of training status on the P/O ratio are limited, with the few investigations showing a similar (Mogensen et al. 2006) or a reduced P/O ratio (Befroy et al. 2008) in trained vs untrained subjects.

Musculo-skeletal structure and mechanics

The mechanical efficiency of running has been shown to exceed the mathematically predicted efficiency of conversion of chemical to kinematic energy within active musculature (Cavanagh and Kram 1985; Williams 1985), indicating a contribution to energy turnover during the running gait that is independent from muscular work. In the stance phase of the running gait, active muscles in the legs contract eccentrically on landing, followed immediately by a concentric contraction during the propulsive phase. During this stretch shortening cycle, energy can be stored during eccentric contractions within the series elastic component of the muscle-tendon unit that can be passively released during the concentric phase of the movement, reducing the net energy requirement of motion. Previous estimates indicate that, whilst running at a moderate speed, the tendons in the arch of the foot and the Achilles tendon can store 17% and 35%, respectively, of the kinetic and potential energy gained and lost in a step; estimated from the responses of an amputated foot model (Ker et al. 1987). Moreover, following mathematical estimations of external and internal work during the running gait, it has been postulated that the energy requirement during running could be 30-40% greater without the contributions from elastic energy storage and subsequent reutilisation (Cavagna et al. 1964). Intuitively, altered structural characteristics of the aponeuroses and tendons around the ankle, knee and hip that enhance storage and return of potential energy during running would induce superior RE.

Theoretically, comparatively short muscles in series with longer, thinner tendons should be conducive for stretch-shortening cycle potentiation; leading to more energy storage and return (Biewener and Roberts 2000), consequently increasing economy. Indeed, a longer Achilles tendon length has recently been shown to correlate with better RE in recreational distance runners (Hunter et al. 2011). Moreover, indirect estimates of stiffness suggest the compliance of the tendons and aponeurosis within the quadriceps femoris could also contribute to energy storage during running (Arampatzis et al. 2006), with a greater compliance reported at low, submaximal force levels for more economic runners (Arampatzis et al. 2006; Fletcher et al. 2010). Moreover, changes in Achillies tendon stiffness have been shown to relate to changes in RE (Fletcher et al. 2010). Yet, a follow up study suggested the relationship between Achilles tendon stiffness and RE might only be evident in female, and not male, runners (Fletcher et al. 2013). However, the sensitivity and validity of indirect assessments of tendon stiffness could be questioned, thus limiting the interpretation of these findings.

In addition to these structural characteristics, the positioning of this connective tissue relative to the joint might also influence RE. A smaller moment arm, defined as the shortest perpendicular distance from the line of action to the centre of rotation, is known to enhance storage of elastic energy (Scholz et al. 2008). For a cohort of well-trained runners, a strong relationship (r=0.75) has been reported between the moment arm of the Achilles tendon and RE at 16 km.h^{-1} (Scholz et al. 2008). Finally, despite prescription of flexibility training by many athletic coaches with an aim of increasing RE (Jones 2002), increased stiffness of the hip and lower limbs has been associated with elevated RE (Gleim et al. 1990; Craib et al. 1996; Jones 2002). Moreover, recent observations indicate that global static stretching of the lower limbs has no acute influence on RE (Allison et al. 2008). It is postulated that the stiffer muscle-tendon and joint complex would not only enhance elastic energy storage and return, but also reduce the range of motion of the pelvic region (Gleim et al. 1990; Craib et al. 1996). Furthermore, the inflexibility of the region might also diminish the additional recruitment of muscle mass required to stabilise the pelvis during impact and the stance phase of running (Gleim et al. 1990). The available evidence therefore suggests, either via training or genetic endowment, ability to store and re-utilise energy within the muscle-tendon unit forms one key construct that contributes to superior RE in elite distance runners.

2.5.2.2 Biomechanical factors

An athlete who employs movement patterns that excludes non-productive movement, exerts forces of appropriate magnitude and direction with precise timing may minimise the work required to sustain a given velocity (Anderson 1996). Investigations have therefore looked to quantify the mechanical descriptors of the running gait, to in turn elucidate whether a distinct mechanical profile for an economical distance runner exists.

Spatiotemporal factors

It is well established that high running speeds are associated with elevated stride lengths, stride frequencies, and a reduction in ground contact time (Cavanagh and Williams 1981; Svedenhag and Sjödin 1994; Weyand and Sternlight 2000). Studies have shown that both self-selected stride length and frequency are often the most economically optimal for a given athlete (Williams and Cavanagh 1987b), potentially mediated by a self-optimising process that migrates towards the lowest RE. However, cross-sectional observations have reported no association between RE and stride length or stride frequency at a given speed (Kyröläinen et al. 2001; Santos-Concejero et al. 2014a).

Previous investigations have also highlighted that greater force generation during the ground contact of the running gait is the primary factor driving the achievement of faster running speeds, rather than the rapid repositioning of lower limbs during the swing phase (Weyand and Sternlight 2000). It could be argued that elongating ground contact time (t_c) may confer a mechanical advantage for endurance athletes by offsetting the requirement of greater rates of force development, reducing the recruitment of faster and more metabolically expensive muscle fibres, thus potentially reducing RE. Indeed, an inverse association (~r=0.5) has been identified between O_C and t_c in distance runners (Williams and Cavanagh 1987a; Roberts and Kram 1998; Di Michele and Merni 2014). It is proposed that 70-90% of the increase in $\dot{V}O_2$ with speed can be explained by the reduction in t_c in humans and bipedal animals (Roberts and Kram 1998). Yet, evidence appears equivocal, with some authors reporting no association (Kyröläinen et al. 2001; Støren et al. 2011) or even a positive relationship between RE and t_c (Paavolainen et al. 1999), with the latter attributed larger decelerations of horizontal speed as t_c increases (Nummella et al. 2007). However, it is also possible that the association between t_c and RE is clouded by the concurrent interaction of other biomechanical influences, such as stride angle (Santos-Concejero et al., 2014) and foot strike patterns (Di Michele and Merni 2014).

During ground contact, muscle activation is required to maintain forward momentum and stability during running. Ground reaction forces (GRF) characterise these functional and mechanical requirements, reflecting the acceleration pattern of the body’s centre of gravity during this stance phase of running. Excessive changes in momentum in the vertical, anterior-posterior and medial-lateral planes can often occur during running (Heise and Martin 2001), elevating the metabolic energy requirement without a functional gain in running velocity. In support of this premise, a strong positive correlation has been reported between vertical impulse measures and O_C in recreational runners (Heise and Martin 2001). Moreover, recent investigations have noted an association of similar strength (r = 0.65) between vertical oscillation and O_C in highly trained distance runners (Tartaruga et al. 2012), indicating those with lower and potentially less wasteful vertical motion display greater RE. It is therefore plausible that minimising excessive force generation in the vertical plane of motion could lead to a reduction in energy expenditure at a given intensity.

Kinematic factors

The extension of the lower leg at toe off has consistently been associated with RE in both cross-sectional and longitudinal investigations (Williams et al. 1987; Williams and Cavanagh 1987b; Moore et al. 2012; Moore et al. 2014). A less extended leg at toe off facilitated by a combination of less knee extension and/or plantar flexion as the foot leaves the ground has been associated with a lower O_C, and thus a superior RE. The greater flexion of the leg is suggested to enhance the propulsive force during toe off (Moore et al. 2012), in addition to reducing the required flexion during the swing phase (Moore 2016).

Stride angle, defined as the angle between of the theoretical tangent of the foot parable from toe off to initial ground contact and the ground (Santos-Concejero et al. 2014a; Santos-Concejero et al. 2014b), has been shown to display a large, negative association with O_C (r=0.8) in highly trained runners (Santos-Concejero et al, 2014a). It is possible that a larger stride angle is associated with superior RE and could be mediated by reducing stride length or increasing swing time.

The initial contact of the foot with the ground has also been associated with RE. Strike patterns can be divided into 3 distinct categories; a fore-foot strike (FF), in which the ball of the foot lands before the heel; a mid-foot strike (MF) in which the heel and the ball of the foot land simultaneously; and a rear-foot strike (RF) in which the heel lands first (Hasegawa 2007; Lieberman et al. 2010). Though studies have identified ~70-80% of shod runners display a RF pattern (Hasegawa 2007; Larson et al. 2011), a MF and FF pattern has been postulated to enhance RE (Hasegawa 2007; Jenkins and Cauthon 2011). The mechanisms underpinning this theory are based on the effective exploitation of the series elastic component, with a more FF pattern enabling greater storage and return of elastic energy in the longitudinal arch of the foot and the Achilles tendon (Perl et al. 2012). Indeed, MF/FF have been shown to be more economical than RF at a given stride angle (<4°; (Paavolainen et al. 1999; Nummela et al. 2006; Santos-Concejero et al., 2014b). Despite this, previous investigations have shown no differences in RE between RF and FF (Ardigo et al. 1995; Cunningham et al. 2010; Perl et al. 2012).

Footwear

Often coupled with foot strike pattern, the shoes employed by endurance runners might have a considerable bearing on RE. For the vast majority of human evolutional history, athletes would have been limited to running barefooted, or in minimally cushioned sandals (Lieberman et al. 2010). Due to elevated collision forces experienced in RF strikes, barefoot and minimally shod runners typically exhibit a MF or FF pattern (Lieberman et al. 2010). However, the additional cushioning in the heel of modern running shoes reduces the impact experienced by the body, allowing a RF strike to be maintained for extended periods without injury. Though it is clear that the choice of shoe may influence strike pattern, and vice versa, evidence suggests footwear may exert an independent effect on RE.

Additional mass carried on the feet clearly increases the inertia of the lower leg and is known to increase the metabolic cost of running, equating to an increase of ~1% in VO_2 for every 100g of mass added (Frederick 1983; Franz et al. 2012). Given that even minimalist shoes weigh ~200g, shod running might be expected to incur an additional metabolic penalty compared to barefoot running if all other factors remain constant (Franz et al. 2012). However, several previous investigations have shown no differences in RE between barefoot and shod running (Frederick 1983; Burkett et al. 1985; Franz et al. 2012). As leg muscles are required to generate force to cushion and stabilise the impacts experienced during the running gait, barefoot running may require greater muscular cushioning and stabilisation that negates any inertial benefits of a lighter lower leg. Indeed, under conditions of equal foot mass, shod running resulted in a ~3% improvement in RE when compared to barefoot running; attributed to a reduced metabolic cost of cushioning (Franz et al. 2012). This theory was later substantiated in a well-designed study that manipulated the running surface, rather than footwear (Tung et al. 2013). Using a modifiable treadmill belt, barefoot running on a cushioned surface (10 mm thickness) resulted in a ~1.7% enhancement in RE when compared to barefoot running on a control, rigid surface (Tung et al. 2013). However, it must be noted that doubling the thickness of the cushioned surface resulted in no benefit in RE over the control condition, suggesting that if the optimal amount of cushioning is exceeded, then excessive dampening may occur (Tung et al. 2013).

2.5.2.3 The influence of surface gradient

It is also well established that surface has a substantial influence on the energetic cost of running (Margaria et al. 1963; Minetti et al. 2002). When running on positive gradients, the body's centre of mass (COM) is elevated during each stride cycle, resulting in a gain in gravitational potential energy at the end of the stance phase when compared to the beginning, increasing the energetic cost for a given running speed (Margaria et al. 1963; Minetti et al. 2002; Snyder and Farley 2011). Moreover, as the increase in E_C is primarily achieved through metabolically expensive concentric contractions, resulting in greater physiological work (Snyder, Kram and Gottschall 2012), and a shift in the emphasis towards metabolic determinants of RE might occur. Conversely, when running downhill a reduced requirement for positive work is evident (Snyder, Kram and Gottschall 2012). Furthermore, a higher vertical velocity on landing during downhill running gives more opportunity for elastic energy storage and re-utilisation (Gottschall and Kram 2005; Yokozawa, Fujii and Michiyoshi 2005; Neves, Johnson and Myrer 2014). Consequently, a reduction in the energetic cost for a given running speed ensues (Margaria et al. 1963; Minetti et al. 2002; Snyder & Farley, 2011), with a potential shift in the emphasis away from metabolic efficiency to mechanical efficiency and the ability to store and re-utilise gravitational potential energy (Snyder, Kram and Gottschall 2012). It would therefore appear that the use of uphill and downhill running might provide a useful diagnostic tool for understanding the determinants and limiting factors to each runner's economy. However, this concept has yet to be investigated.

2.5.2.4 Possible influence of $\dot{V}O_{2max}$ on running economy

The translation of an individual's maximal aerobic capacity into linear velocity, commonly defined as the velocity at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$), has been of considerable interest since its conception. This variable encompasses both RE and $\dot{V}O_{2max}$, providing an estimate of the running velocity mathematically associated with attainment of $\dot{V}O_{2max}$ (Daniels 1985). It is suggested that $v\dot{V}O_{2max}$ provides a useful tool to explain performance similarities between athletes who possess different levels of $\dot{V}O_{2max}$ and RE (Daniels 1985; Morgan et al. 1989). Unsurprisingly, the $v\dot{V}O_{2max}$ has been shown to be the strongest predictor of endurance performance in cohorts heterogeneous cohorts for performance ability (Morgan et al. 1989; McLaughlin et al. 2010), accounting for ~94% of the inter-individual variance in 16 km performance (McLaughlin et al. 2010). Given the contribution of both RE and $\dot{V}O_{2max}$ to $v\dot{V}O_{2max}$, simultaneous enhancement of these underpinning constructs are likely to result in substantial performance gains. However, previous investigations have noted an inverse relationship exists between RE and $\dot{V}O_{2max}$ in populations of trained endurance athletes (Pate et al. 1992; Morgan and Daniels 1994; Sawyer and Blessinger 2010).

In a cross sectional examination of 178 trained runners, Pate and colleagues (1992) noted a positive relationship ($r = 0.26$) between submaximal $\dot{V}O_2$, assessed at 6 mph, and $\dot{V}O_{2max}$. Though seemingly paradoxical, these findings were later confirmed in elite cohorts ($r = 0.59$; Morgan and Daniels 1994) and physically active individuals ($r = 0.48$; Sawyer and Blessinger 2010). These findings have led to theories that the inherent association between RE and $\dot{V}O_{2max}$ results from $\dot{V}O_2$ being a consequence, rather than a determinant, of athletic ability (Noakes and Tucker 2004). Athletes displaying superior athletic ability will achieve greater peak work rates, with the resultant $\dot{V}O_{2max}$ being dependent on the economy of the individual at this speed (Noakes and Tucker 2004). Consequently, it has been proposed that in cohorts homogenous for endurance performance, an inverse relationship is likely to be found (Lucia et al. 2003; Noakes and Tucker 2004). However, the cohorts of the aforementioned investigations are truly 'homogenous' for performance should be questioned, as notable variability in performances would still be expected even in cohorts of highly trained athletes. Moreover, studies have solely employed cross sectional comparisons to assess the interactions of RE and $\dot{V}O_{2max}$. Longitudinal assessment of both RE and $\dot{V}O_{2max}$ in endurance athletes could give further insight into whether an inherent association exists between these two variables.

Due to repeated reports of this positive relationship between RE and $\dot{V}O_{2max}$, several theories have been proposed to explain an inherent association between the two variables. Previous investigations have highlighted a negative relationship between submaximal RER and $\dot{V}O_{2max}$, indicating a greater reliance on fat oxidation during submaximal efforts in those individuals with high aerobic capacities (Costill et al. 1979; Pate et al. 1992). Given the lower energy equivalent of O_2 for lipids when compared to carbohydrates (Krogh and Lindhard 1920), the greater reliance on this energy substrate is likely to elevate submaximal $\dot{V}O_2$ for such individuals. In addition, muscle fibre composition has also been implicated as a factor underpinning this relationship. Though increasing the aerobic capacity, an increased proportion of type IIa fibres within the gastrocnemius may increase the submaximal oxygen demand, due to the relative inefficiency of this fibre type (Hunter et al. 2001). It is therefore possible that those with greater $\dot{V}O_{2max}$ display a greater proportion of these type IIa fibres, thus incurring an additional metabolic penalty during submaximal running (Sawyer and Blessinger 2010). However, there is considerable evidence that $\dot{V}O_{2max}$ during whole body exercise is largely determined by oxygen delivery, rather than demand and utilisation within the active musculature (Wagner 2000), which might question this explanation.

It should be noted that the restricted body of evidence exploring the relationship between RE and $\dot{V}O_{2max}$ is not without limitation. Studies have often employed small sample sizes (<25 participants (Morgan and Daniels 1994; Lucía et al. 2002; Fletcher et al. 2009) that is likely to have compromised the statistical strength of the relationship between $\dot{V}O_{2max}$ and RE (Morgan and Daniels 1994; Lucía et al. 2002). More prominently, the employment of inappropriate statistical techniques could create spurious relationships between these two variables. Due to the known influence of body mass on both RE and $\dot{V}O_{2max}$, studies have often expressed both variables relative to the mass of the individual (Pate et al. 1992; Morgan and Daniels 1994; Sawyer and Blessinger 2010). When examining the relationship between these two variables, it is possible that BM acts as a common divisor, establishing a correlation between these two variables even in the absence of any ‘organic’ link (Atkinson et al. 2003). Therefore, similar correlations to those reported in the aforementioned studies would be apparent even when random values of $\dot{V}O_2$ are generated and expressed relative to BM (Atkinson et al. 2003). Consequently, the existence of this relationship may merely reflect a statistical artefact, inherently associated by calculation. Exploring the relationship between RE and $\dot{V}O_{2max}$ with appropriate statistical methods could in turn explicate the true relationship between these variables.

2.5.3 **Training to enhance running economy**

The greater physiological capability possessed by elite endurance athletes is a composite of natural genetic endowment (Smith 2003; Bray et al. 2009; Ahmetov et al. 2009) and chronic adaptations from physical training (Midgley et al. 2007; Laursen 2010). Although the genetic make-up of an individual represents an unalterable construct, the modulation of exercise training is known to have profound effects on physical adaptation and athletic performance (Holloszy and Coyle 1984; Hawley 2002; Hawley and Spargo 2007). The magnitude of this training response is dependent on the intensity, duration and frequency of exercise bouts (Wenger and Bell 1986), in addition to initial training status, genetic potential, age and gender of the individual (Jones and Carter 2000). It might therefore be considered that while genetics might set the boundaries of an individual's athletic capacity, physical training determines the extent to which this athletic potential is realised. Consequently, effective training practices to improve RE are likely to be vital to achieving success in endurance running.

2.5.3.1 Run training intensity

Substantial improvements in RE have previously been noted in a longitudinal analysis of an elite endurance runner (Jones 2006), highlighting the trainability of this variable. Continual exposure to high training volumes over extended time periods have previously been proposed as a substantial contributing factor to enhancements in RE (Morgan and Bransford 1995). Subtle alterations to mechanical efficiency and running technique in response to repeated contractions during submaximal training bouts might progressively accumulate in the long term (Nelson and Gregor 1976), leading to significant enhancements in RE. Furthermore, this neuromuscular entrainment might exhibit a degree of velocity specificity, with anecdotal reports of athlete's displaying their best RE over the velocities at which they habitually train (Jones and Carter 2000). However, the specificity of training velocity on RE has yet to be investigated.

The inclusion of high-intensity interval training has previously been shown to enhance RE of well-trained runners (Billat et al. 1999; Slawinski et al. 2001). Over a 4 week intervention, RE was seen to improve by ~6.5% with the incorporation of intense weekly interval sessions at $v\dot{V}O_{2max}$ into a normal training programme (Billat et al. 1999). Likewise, an ~4% enhancement was observed following 8 weeks of short duration interval training at supra-lactate threshold intensities (Slawinski et al. 2001). Moreover, an ~7% increase in RE has been noted following 4 weeks of supplementary training at the velocity associated with LTP (vLTP) in already highly trained runners (Billat et al. 2004). However, it is important to note that no control groups were employed in the aforementioned investigations, compromising the interpretation of these findings. Moreover, although these findings suggest that training at or around vLTP and v$\dot{V}O_{2max}$ might induce enhancements in RE, the findings from an investigation with recreationally active individuals suggest that supra-maximal velocities might be ineffective in eliciting comparable responses (Franch et al. 1998). It is possible that an inability to accomplish a sufficient training volume at supra-maximal intensities, in addition to a loss of running form, might limit the training response to such intensities (Midgley et al. 2007).

2.5.3.2 Resistance and plyometric training

A large body of evidence exists suggesting the incorporation of concomitant strength training into an existing endurance training programme results in significant improvements in RE. Enhancements of 4-7% in RE have been observed with the inclusion of traditional strength training, comprising of high resistive loads and low repetitions, in already well trained endurance athletes (Johnston et al. 1997; Millet et al. 2002). However, long term training of this nature is known to evoke substantial increases in body mass (Abe et al. 2003), that could in turn be detrimental to endurance performance (Costill 1967). On the contrary, plyometric training (PT) is known to elicit similar muscular adaptations with markedly lower levels of hypertrophy to that of traditional strength training (Häkkinen et al. 1985; Sale 1991). Following a 9 week inclusion of PT into the habitual training of highly trained endurance runners, substantial improvements in RE (4-8%) have been reported (Paavolainen et al. 1999; Saunders et al. 2006). In addition to possible neural adaptations, the enhancement in RE resulting from PT is thought to be mediated by an increased stiffness of the muscle-tendon unit; enabling greater recycling of elastic energy during the stretch-shortening cycle (Spurrs et al. 2003).

2.5.3.3 Altitude training

Improvements in RE have been noted following periods of altitude acclimatisation for elite endurance athletes (Saunders et al. 2004c; Schmitt et al. 2006; Saunders et al. 2009). Reductions in submaximal oxygen by 3-4% have been observed in response to relatively short time frame (20-40 days) of live high, train low altitude exposure, inferring an increase in RE (Saunders et al. 2004c; Saunders et al. 2009). Moreover, 5 weeks of intermittent hypoxic exposure incorporated into existing training programmes have been demonstrated to enhance RE greater than training alone during pre-season training (Burtscher et al. 2010).

However, the precise mechanisms underpinning the improvements in RE following altitude exposure are unclear.

2.6 **Summary**

This critical review of the literature has highlighted clear scope for further investigations that could enhance the understanding of running economy in trained athletes. The objective of this thesis was to therefore provide a comprehensive analysis of the RE of highly trained runners, from its quantification, to potential factors that affect RE, and finally an intervention that could enhance this RE in this specific population. This was addressed through the following aims:

- To identify a reliable (Chapter 3) and valid (Chapter 4) method to assess and quantify running economy in trained distance runners.
- To assess the variability in the running economy responses of athletes when running on positive and negative gradients (Chapter 5).
- To explore the cross-sectional and longitudinal relationship between running and maximal oxygen uptake (Chapter 6).
- To assess the efficacy of downhill running as a training method to enhance running economy in highly trained distances runners (Chapter 7)

CHAPTER III

The reliability of running economy expressed as oxygen cost and energy cost in trained distance runners

3.1 Introduction

For distance running, maximal oxygen uptake ($\dot{V}O_{2max}$), the proportion of $\dot{V}O_{2max}$ that can be sustained prior to the onset of blood lactate accumulation and the metabolic cost of locomotion are the primary physiological factors that underpin performance (Pollock 1977; Farrell et al. 1979; Ingham et al. 2008). The latter, quantified as the oxygen cost or energy cost for a given submaximal velocity, defines an individual's running economy. In an athletically homogenous population, running economy is cited as a stronger indicator of endurance performance than $\dot{V}O_{2max}$ alone (Conley and Krahenbuhl 1980; Daniels 1985), and it has been suggested that modest enhancements in running economy could result in substantial performance gains for elite distance runners (Cavanagh 1989). Accordingly, improvements in running economy are highly desirable in order to maximise athletic performance. However, without prior knowledge of the between test reliability of running economy, interpretation of any changes is limited.

Measurements of running economy are made during submaximal steady state exercise in order to provide an index of adenosine triphosphate (ATP) turnover when aerobic metabolism supplies virtually all of the energy requirements. The most commonly employed measure of running economy is oxygen cost (O_C), defined as the oxygen required to cover a given distance (Foster and Lucia 2007; Ingham et al. 2008), and has been reported to have a typical error of 4.7 and 2.4% in elite distance runners (Brisswalter and Legros 1994b; Saunders et al. 2004a). However, as there are differences in the O_C of metabolising carbohydrates and lipids (Krogh and Lindhard 1920), alterations in substrate utilisation could influence, and potentially confound, the reliability of running economy.

The use of energy cost (E_C) has been used as an alternative measure of running economy (Margaria et al. 1963; Folland et al. 2006; Allison et al. 2008) that has been postulated to be a more comprehensive, sensitive and valid measure (Fletcher et al. 2009), as it calculates actual energy expenditure, from O_C and the RER, and thus accounts for variations in substrate metabolism. To minimise between test reliability of O_C, previous studies have typically employed a range of experimental controls, including restrictions on prior training and nutrition (Williams et al. 1991; Brisswalter and Legros 1994b; Pereira and Freedson 1997), in order to control for variations in substrate metabolism. However, for the monitoring of athletes in full time training, these experimental controls are frequently impractical and may not be necessary if E_C is the primary measurement of running economy. Accordingly, quantification of running economy as E_C might mitigate the confounding influence of substrate utilisation on O_C, providing greater reliability without imposing practical constraints on the participant. We therefore hypothesised that E_C would provide a more reliable measure of running economy than O_C.

To aid the practical interpretation of between-test reliability, it is useful to compare the typical error to the smallest worthwhile change (SWC). The SWC reflects the smallest individual change that can be interpreted as real within acceptable limits of probability (Impellizzeri and Marcora 2009), representing the threshold for when a change becomes ‘meaningful’. Comparisons of the typical error to SWC enable investigators to assess if a test is sufficiently reliable to detect the SWC. Consequently, if the typical error > SWC, it is not possible to confidently detect the SWC due to the insufficient reliability of the test. A previous investigation suggested that absolute measurements of O_C ($L \cdot min^{-1}$) were sufficiently reliable to detect the SWC (Saunders et al. 2004). However, the metabolic cost of running is known to be proportional to body mass (BM), and relative values enable accurate comparisons between individuals of differing BM (Bergh et al. 1991; Svedenhag 1995), which is not the case for absolute values. As the calculation of the SWC relies on the assessment of inter-individual differences, the expression of running economy relative to $BM^{0.75}$ would appear the most appropriate measurement. However, whether quantification of running economy relative to BM provides sufficient reliability to detect the SWC remains unknown.

Therefore, the primary aim of the present study was to examine the between test reliability of oxygen and energy cost measurements of running economy. Highly trained competitive runners were assessed using a widely used short-duration incremental submaximal running protocol, but without specific training or dietary restrictions, to examine if these controls might be circumvented by the potentially more reliable E_C assessment of running economy. The secondary aim was to contrast the reliability of O_C and E_C measurements with the SWC for these measures.

3.2 Materials and methods

3.2.1 Participants

Twelve healthy endurance trained males (mean ± SD: age 28 ± 6 y, stature 180 ± 5 cm, BM 70.6 ± 3.4 kg, $\dot{V}O_{2max}$ 75.5 ± 5.2 $ml\cdot kg^{-1}\cdot min^{-1}$) participated in this study. Participants' best performances times over the past two seasons were 114 ± 5% of the current British record as of December 2012 in events from 1500m to the marathon. All participants were treadmill habituated and provided written informed consent prior to participating in this study, which was approved by the Loughborough University Ethical Advisory Committee. Observations on a larger cohort of twenty nine endurance trained males (age 24 ± 7 y, BM 67.9 ± 7.5 kg, $\dot{V}O_{2max}$ 73.4 ± 6.1 $ml\cdot kg^{-1}\cdot min^{-1}$) were used to determine the SWC.

3.2.2 Overview

Participants attended the laboratory on four separate occasions. The first three visits were for identical submaximal running trials conducted 7 days apart at a consistent time of day for each participant. A final visit involved a maximal treadmill running assessment. Participants wore appropriate clothing and racing shoes and laboratory conditions were similar throughout all running assessments (temperature 19-21°C, relative humidity 40-50%). The SWC was assessed using single observations of 29 runners using the same protocol employed for the reliability measurements.

3.2.3 Protocol

Submaximal running assessments

Following a warm-up (10 minutes at 10-11.5 $km\cdot h^{-1}$), participants completed a discontinuous submaximal incremental test of seven 3 minute stages with increments of 1 $km\cdot h^{-1}$ on a calibrated motorised treadmill (HP cosmos Saturn, Traunstein, Germany) at 1% gradient, interspersed by 30 s rest periods for blood sampling. The heart rate (HR) response during the warm-up was used to determine a starting speed and provide a minimum of 4 speeds prior to lactate turnpoint (LTP). HR (s610i, Polar, Finland) and pulmonary gas exchange (detailed below) were monitored throughout the test.

Maximal running assessments

$\dot{V}O_{2max}$ was determined by a continuous incremental treadmill running ramp test to volitional exhaustion. After a warm-up, participants initially ran at a speed 2 $km \cdot h^{-1}$ below the final speed of the submaximal test and at a 1% gradient. Each minute, the incline was increased by 1% until volitional exhaustion. The test duration was typically 6-8 minutes.

3.2.4 **Measurements**

Anthropometry

Prior to exercise on all laboratory visits, BM was measured using beam balance scales to the nearest 0.1 kg. Stature was recorded to the nearest 1 cm using a stadiometer.

Pulmonary gas exchange

Breath-by-breath gas exchange data were quantified via an automated open circuit metabolic cart (Oxycon Pro, Carefusion, San Diego, USA). Participants breathed through a low-dead space mask, with air sampled at 60 $ml \cdot min^{-1}$. Prior to each test, two point calibrations of both gas sensors were completed, using a known gas mixture (16% O_2, 5% CO_2) and ambient air. Ventilatory volume was calibrated using a 3 L (±0.4%) syringe. Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and RER values were quantified over the final 60 s of each stage of the submaximal protocol. To assess if a steady-state for $\dot{V}O_2$ and $\dot{V}CO_2$ had been attained (defined as a difference of <5.8 $ml \cdot kg^{-0.75} \cdot min^{-1}$; equivalent to 2 $ml \cdot kg^{-1} \cdot min^{-1}$) during the final minute of each stage during the first assessment, the first and last 30 s of this final minute were compared. Gas exchange data were collected throughout the maximal running assessment test, with $\dot{V}O_{2max}$ defined as the greatest continuous sample of $\dot{V}O_2$ averaged over 30 s.

Blood lactate

A 20 µl capillary blood sample was taken from the earlobe for analysis of blood lactate ($[La]_b$) (Biosen C-line, EKF diagnostics, Germany). The LTP was identified to the nearest $km \cdot h^{-1}$ from $[La]_b$ vs. speed relationship. LTP was defined as the running speed above which $[La]_b$ increased by >1.0 $mmol \cdot l^{-1}$ from the previous stage (Thoden 1991). The four stages prior to LTP were identified for each participant (LTP-4, -3, -2 and -1 $km \cdot h^{-1}$) and used to assess the O_C and E_C of running.

Calculation of running economy

$\dot{V}O_2$ during the final minute of each submaximal stage was used to determine O_C in $mL\cdot kg^{-0.75}\cdot km^{-1}$. $\dot{V}O_2$ and $\dot{V}CO_2$ during the same time period were used to calculate E_C. Updated nonprotein respiratory quotient equations (Péronnet and Massicotte 1991) were used to estimate substrate utilisation ($g\cdot min^{-1}$) during the monitored period. The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolised substrates during moderate to high intensity exercise (Jeukendrup and Wallis 2005). E_C was quantified as the sum of these values, expressed in $kcal\cdot kg^{-0.75}\cdot km^{-1}$. A worked example of this process is provided below for a 70 kg athlete running at 14 $km\cdot h^{-1}$ with a $\dot{V}O_2$ of 3.5 $L\cdot min^{-1}$ and $\dot{V}CO_2$ of 3.0 $L\cdot min^{-1}$

Fat utilisation

$(1.695 * 3.5) – (1.701 * 3.0) = 0.83\ g\cdot min^{-1}$ Energy derived = $0.83 * 9.75 = 8.09\ Kcal\cdot min^{-1}$

Carbohydrate utilisation

$(4.585 * 3.0) – (3.226 * 3.5) = 2.46\ g\cdot min^{-1}$ Energy derived = $2.46 * 4.07 = 10.01\ Kcal\cdot min^{-1}$

Total energy

$8.09 Kcal\cdot min^{-1} + 10.01\ Kcal\cdot min^{-1} = 18.10\ Kcal\cdot min^{-1}$

$(18.10\ Kcal\cdot min^{-1} * 60) / 14\ km\cdot h^{-1}= 77.57\ Kcal\cdot km^{-1}$

Expressed to body mass

$77.57\ Kcal\cdot km^{-1} / 70kg^{(0.75)} = 3.21\ Kcal\cdot kg^{-1}\cdot min^{-1}$

Both O_C and E_C were also quantified in absolute terms ($L\cdot km^{-1}$ and $kcal\cdot km^{-1}$ respectively) enabling comparisons of the SWC to previously published data.

3.2.5 **Statistical analyses**

Normal distributions of the dependant variables were confirmed via Shapiro-wilk tests, and the variance was found to be homogenous for the assessed speeds. Two-way ANOVA with repeated measures were used to assess differences in all monitored variables across trials and speeds. To assess intra-individual variation between tests, the typical error (TE), a value that encompasses both technical and biological variation, was calculated using the root mean squares error method (Batterham 2003). The reliability of E_C and O_C was also assessed via intraclass correlation coefficients (ICC, two-way random, single measure). To enable the statistical comparison (two-way ANOVA) of within-subject variation to be made between measures, the within-subject coefficients of variations (CV_W) were calculated for each individual ([Standard deviation /mean]*100). The SWC in measures of E_C and O_C was calculated as 0.2 times the between-participant standard deviation within the larger cohort (*n*=29; Hopkins 2000). The between-participant coefficient of variation (CV_B) for $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated from this cohort. Data are presented as mean ± standard deviation, with significance accepted at $p \leq 0.05$.

3.3 Results

BM remained consistent across the submaximal assessments (70.6 ± 3.4, 70.6 ± 3.3, 70.8 ± 3.4 kg; p = 0.46), with a mean CV_W of 0.55 ± 0.31% across the 3 trials. Mean LTP was 17 ± 1 $km \cdot h^{-1}$ for the cohort. $\dot{V}O_2$, RER and $[La]_b$ were similar across all trials at each given speed. Low levels of within-subject variation were seen for HR (TE <3.25%), $\dot{V}CO_2$ (TE <5.94%), RER (TE <4.35%), and $\dot{V}O_2$ (TE <3.33%) across the submaximal assessments. Within-subject variability for $[La]_b$ was high for all monitored speeds (TE 18.3–24.4%), but absolute group mean values were stable (<0.4 $mmol \cdot L^{-1}$ change between trials).

Differences in gaseous exchange between the first and final 30 s of the monitored minute were small for both $\dot{V}O_2$ and $\dot{V}CO_2$ (group mean differences <2.02 $mL \cdot kg^{-0.75} \cdot min^{-1}$ across all speeds). Of the 48 assessments of gaseous exchange for the first trial (12 runners × 4 stages), the steady-state criteria were not met on 2 ($\dot{V}O_2$) and 5 ($\dot{V}CO_2$) occasions. However, when such cases did occur, differences did not exceed 8 $ml \cdot kg^{-0.75} \cdot min^{-1}$ (equivalent to 2.8 $ml \cdot kg^{-1} \cdot min^{-1}$). Within-subject variation was greater for $\dot{V}CO_2$ (CV_W 4.06 - 5.35%) than $\dot{V}O_2$ (CV_W 2.29 - 2.98%; p < 0.01).

No systematic bias was observed for any measure of running economy (O_C or E_C in absolute or relative values) across the 3 weeks (p > 0.37). Absolute and relative E_C were lower for LTP-4 than LTP-3 and LTP-1 (Table 3.1), however O_C was similar across all speeds. Within-subject variation was low for all measures of running economy across the submaximal assessments (TE < 3.85%; Table 3.1).

Table 3.1. Reliability of running economy measures collected during the submaximal running assessments. Data are displayed as Mean ± SD (*n* = 12).

Measurement Speed	**Trial**			**TE**	**TE (%)**	**ICC**
	1	2	3			
Oxygen Cost (LO$_2$·km^{-1})						
LTP -4 km·h^{-1}	16.22 ± 1.46	15.94 ± 1.05	15.87 ± 0.94	0.53	3.34	0.79
LTP -3 km·h^{-1}	16.11 ± 1.33	15.99 ± 1.02	16.06 ± 0.98	0.50	3.24	0.81
LTP -2 km·h^{-1}	16.02 ± 1.18	15.97 ± 0.98	16.16 ± 0.98	0.45	2.86	0.82
LTP -1 km·h^{-1}	16.11 ± 1.25	15.96 ± 0.96	16.20 ± 0.89	0.43	2.73	0.84
Mean of the 4 speeds	**16.12 ± 1.28**	**15.96 ± 0.98**	**16.06 ± 0.93**	**0.45**	**2.89**	
Oxygen Cost relative to BM (mlO·kg$^{-0.75}$·km^{-1})						
LTP -4 km·h^{-1}	666.5 ± 58.7	654.7 ± 43.9	651.0 ± 39.8	21.3	3.31	0.82
LTP -3 km·h^{-1}	662.2 ± 53.1	656.6 ± 41.7	658.4 ± 36.6	20.2	3.18	0.82
LTP -2 km·h^{-1}	658.3 ± 45.1	655.5 ± 37.0	662.5 ± 37.1	18.5	2.86	0.81
LTP -1 km·h^{-1}	662.1 ± 48.8	655.4 ± 36.5	662.3 ± 34.4	17.6	2.72	0.83
Mean of the 4 speeds	**662.3 ± 50.3**	**655.6 ± 38.9**	**658.5 ± 36.2**	**18.4**	**2.88**	
Energy Cost (kcal·km^{-1})						
LTP -4 km·h^{-1}	84.27 ± 7.29	82.43 ± 5.98	82.31 ± 4.57	3.17	3.83	0.73
LTP -3 km·h^{-1}*	84.70 ± 7.13	83.43 ± 5.77	84.20 ± 5.08	2.91	3.53	0.78
LTP -2 km·h^{-1}	84.70 ± 6.05	83.95 ± 5.72	85.14 ± 5.33	2.71	3.27	0.78
LTP -1 km.h^{-1}*	86.35 ± 6.81	84.40 ± 5.56	85.51 ± 4.58	2.75	3.28	0.76
Mean of the 4 speeds	**85.01 ± 6.72**	**83.56 ± 5.63**	**84.30 ± 4.76**	**2.70**	**3.27**	
Energy Cost relative to BM (kcal·kg$^{-0.75}$·km^{-1})						
LTP -4 km·h^{-1}	3.463 ± 0.297	3.385 ± 0.240	3.375 ± 0.180	.126	3.72	0.75
LTP -3 km·h^{-1}*	3.481 ± 0.287	3.426 ± 0.229	3.452 ± 0.182	.115	3.39	0.79
LTP -2 km·h^{-1}	3.480 ± 0.233	3.447 ± 0.214	3.494 ± 0.192	.108	3.16	0.78
LTP -1 km·h^{-1}*	3.549 ± 0.281	3.465 ± 0.210	3.514 ± 0.175	.106	3.05	0.79
Mean of the 4 speeds	**3.493 ± 0.240**	**3.431 ± 0.218**	**3.459 ± 0.176**	**.106**	**3.13**	

*- denotes a significant difference to LTP -4 km·h^{-1} when collapsed across trials. BM, body mass; ICC, intraclass correlation coefficient; LTP, lactate turnpoint; TE, typical error

Table 3.2. Smallest worthwhile changes in oxygen cost and energy cost assessed at the 4 speeds prior to LTP (n = 29).

Measurement Speed	**Economy**	**CV_B** (%)	**SWC**	**SWC** (%)
Oxygen Cost ($LO_2 \cdot km^{-1}$)				
LTP -4 $km \cdot h^{-1}$	15.02 ± 2.220	14.8	0.44	2.96
LTP -3 $km \cdot h^{-1}$	14.96 ± 2.089	14.0	0.42	2.79
LTP -2 $km \cdot h^{-1}$	14.90 ± 1.999	13.4	0.40	2.68
LTP -1 $km \cdot h^{-1}$	14.93 ± 1.960	13.1	0.39	2.63
Mean of the 4 speeds	**14.95 ± 2.058**	**13.8**	**0.41**	**2.75**
Oxygen Cost relative to BM ($mlO_2 \cdot kg^{-0.75} \cdot km^{-1}$)				
LTP -4 $km \cdot h^{-1}$	632.6 ± 50.21	7.9	10.0	1.59
LTP -3 $km \cdot h^{-1}$	630.6 ± 45.21	7.2	9.04	1.43
LTP -2 $km \cdot h^{-1}$	628.1 ± 41.86	6.7	8.37	1.33
LTP -1 $km \cdot h^{-1}$	629.6 ± 39.66	6.3	7.93	1.26
Mean of the 4 speeds	**630.3 ± 43.50**	**6.9**	**8.70**	**1.38**
Energy Cost ($kcal \cdot km^{-1}$)				
LTP -4 $km \cdot h^{-1}$	79.66 ± 11.43	14.3	2.29	2.87
LTP -3 $km \cdot h^{-1}$	80.17 ± 10.97	13.7	2.19	2.74
LTP -2 $km \cdot h^{-1}$	80.65 ± 10.74	13.3	2.15	2.66
LTP -1 $km \cdot h^{-1}$	82.47 ± 11.86	14.4	2.37	2.88
Mean of the 4 speeds	**80.74 ± 11.07**	**13.7**	**2.21**	**2.74**
Energy Cost relative to BM ($kcal \cdot kg^{-0.75} \cdot km^{-1}$)				
LTP -4 $km \cdot h^{-1}$	3.355 ± 0.276	8.2	.055	1.65
LTP -3 $km \cdot h^{-1}$	3.382 ± 0.277	8.2	.055	1.64
LTP -2 $km \cdot h^{-1}$	3.405 ± 0.305	9.0	.061	1.79
LTP -1 $km \cdot h^{-1}$	3.481 ± 0.356	10.2	.071	2.04
Mean of the 4 speeds	**3.406 ± 0.292**	**8.6**	**.058**	**1.71**

BM, body mass; $CV_{B,}$ between-subject coefficient of variation; LTP, lactate turnpoint; SWC, smallest worthwhile change

However, no differences in relative or absolute CV_W between measures of O_C and E_C were evident. ICC analysis revealed significant relationships for all measures of running economy between trials, with values of 0.73-0.84 for O_C and E_C, but no notable differences were observed between the two measures. The SWC was similar between O_C and E_C at all monitored speeds when expressed as a percentage of mean values (Table 3.2). The SWC was notably greater for absolute than relative expressions of O_C (absolute, 2.63 - 3.96% vs relative, 1.26 - 1.59%) and E_C (absolute, 2.66 - 2.88% vs relative, 1.64 – 2.04%) over all monitored speeds. The CV_B for absolute measures were greater than relative expressions (~2-fold) for both O_C and E_C

3.4 **Discussion**

The results of the present study demonstrated similar between-test reliability for O_C and E_C in highly trained distance runners. Moreover, absolute and relative expressions of running economy displayed similar levels of between-test reliability. For relative values that enable accurate comparisons between individuals, the typical error exceeded the SWC for both O_C and E_C. Therefore, the current protocol does not provide sufficient sensitivity to detect small, but meaningful, changes in O_C and E_C when expressed relative to $BM^{0.75}$.

The findings of this study are in accordance with those previously published in this area, with similar levels of between test reliability for the O_C of running relative to BM (Williams et al. 1991; Brisswalter and Legros 1994b). We found the typical error for relative O_C (~ 2 to 3 %) to be similar to a previous study of elite endurance athletes (2.4%); where only time of day and footwear were controlled (Saunders et al. 2004). Conversely, these values were greater than those previously observed for well trained (1.32%) and highly trained (1.77%) endurance athletes that employed dietary and training constraints prior to running economy measurements (Morgan et al. 1991; Pereira and Freedson 1997). It is likely the additional restrictions on the athlete’s day-to-day lifestyle contributed to the enhanced between test reliability of these studies. It was hypothesised that E_C may be a more reliable measure of running economy than O_C, and also compensate the need for stricter experimental controls that can interfere with the full-time training of high performance athletes. Specifically, the quantification of running economy as E_C was proposed to mitigate the confounding influence of alterations in substrate utilisation on O_C in the absence of dietary or training constraints.

The between-test reliability of running economy when quantified as E_C has not been previously documented. E_C exhibited typical error values of <3.9% and ICC values >0.7 for all monitored speeds, and contrary to our hypothesis, had similar between-test reliability as O_C, when expressed in both absolute (mean of 4 speeds: E_C 3.27% vs O_C 2.89%) and relative terms (E_C 3.13% vs O_C 2.88%). Due to the extensive training schedules of the current cohort, variability in substrate metabolism and thus the O_C of running was expected, but not observed, despite the lack of dietary and training controls employed in this study. Intuitively, the stability of substrate utilisation across trials may have obviated the potential benefits of expressing running economy as E_C over O_C. In addition, the reliability of E_C measurements is dependent upon the consistency of both $\dot{V}O_2$ and $\dot{V}CO_2$ recordings (in order to derive RER) rather than just the single measurement ($\dot{V}O_2$) for O_C. It is possible the additional requirement of $\dot{V}CO_2$ might have exacerbated the inherent technical variance in E_C measurements, as the within-subject variation of $\dot{V}CO_2$ was greater than $\dot{V}O_2$. As $\dot{V}CO_2$ exhibits a greater time constant (~50-60s) relative to $\dot{V}O_2$ (~30-40s) during the transition from rest to moderate intensity exercise (Whipp 2007), it is possible that the 3 minute stages employed in the current study were insufficient to establish a genuinely steady state $\dot{V}CO_2$. Consequently, although a theoretical basis for quantifying running economy as E_C is clear, the practical application in the current protocol may explain the lack of any improvement in between test reliability compared to O_C.

To facilitate the practical interpretation of the reliability findings in the current study, the typical error was compared to the SWC calculated from a larger cohort of highly trained endurance runners. When averaged over the four monitored speeds, the typical error for O_C (2.88%) and E_C (3.13%) expressed relative to $BM^{0.75}$, were substantially higher than the SWC (O_C, 1.38%; E_C, 1.71%). Therefore, it appears that the incremental running protocol employed in the current investigation provides inadequate reliability to detect the SWC. This may appear contrary to a previous investigation, however Saunders et al (2004) compared the typical error to the SWC for absolute values of O_C (both 2.4%), rather than the recommended expression of values relative to BM for inter-individual comparisons. Interestingly, the typical error in this study for both absolute O_C (2.89%) and E_C (3.27%) were also similar to the SWC (O_C, 2.74%; E_C, 2.75%), and appears to be an artefact of the greater inter-individual variation of running economy values that are not corrected for BM (e.g. CV_B: O_C, 13.8%; E_C, 13.7%) compared to more appropriate relative values (CV_B: O_C, 6.9%; E_C, 8.6%). Therefore, when expressed relative to $BM^{0.75}$, the current protocol displays insufficient sensitivity to detect the SWC of E_C or O_C. Consequently, investigators employing the 3 minute discontinuous submaximal test examined can only be confident of a true change in running economy when changes >2.9% or >3.1% are apparent for O_C and E_C, respectively.

3.5 Conclusion

Running economy expressed as an O_C and E_C provided similarly high levels of reliability for highly trained endurance runners when assessed using a short-duration incremental submaximal exercise protocol. However, the typical error of measures of O_C and E_C relative to $BM^{0.75}$ was found to be ~2-fold higher than the SWC of both variables. Therefore, only when alterations in O_C or E_C exceed the typical error can practitioners confidently interpret a meaningful change in running economy. As E_C provides similar levels of reliability, and appears to offer greater validity than O_C (Fletcher et al. 2009), it is recommended as the primary measure of running economy.

CHAPTER IV

The valid measurement of running economy in runners

4.1 Introduction

Running economy (RE), defined as the metabolic cost to cover a given distance, is a primary physiological determinant of endurance running performance (di Prampero 2003; Ingham et al. 2008). RE represents the translation of energy turnover into running velocity, and in athletically homogenous populations is cited as a stronger indicator of endurance performance than $\dot{V}O_{2max}$ alone (Conley and Krahenbuhl 1980; Daniels 1985). Moreover, the recent dominance of East Africans in distance running events has been attributed to the superior RE of this population (Larsen 2003; Lucia et al. 2006). Given the fundamental contribution of RE to human locomotion and performance, assuring the validity of RE measurements appears essential.

Previous investigations have considered inter-individual comparisons to identify the specific anthropological, mechanical and physiological factors that characterise an economical runner (Pate et al. 1992; Lucia et al. 2006). These studies have typically measured the RE as the oxygen cost of running (O_C), defined as the oxygen required to cover a given distance (Foster and Lucia 2007; Ingham et al. 2008; Tam et al. 2012) or to maintain a given speed (Saunders et al. 2004a). This quantification of RE is based on the assumption that O_C provides an index of adenosine triphosphate turnover during submaximal exercise, and thus reflects the underlying energy cost (E_C) of locomotion. However, a recent investigation has brought into question the validity of O_C to assess RE, with evidence suggesting a disparity exists between the changes in O_C and E_C as running speed increases (Fletcher et al. 2009). Whilst the E_C to cover a kilometre ($Kcal \cdot kg^{-1} \cdot km^{-1}$) appears to be positively related to speed (Fletcher et al. 2009), O_C has consistently been shown to be independent of running speed (Margaria et al. 1963; Hagberg and Coyle 1984; di Prampero et al. 2009; Fletcher et al. 2009). If such a relationship exists between E_C and running speed, but not for O_C and speed, then the validity of O_C as a measure of RE would appear to be compromised. It is worth noting that Fletcher and colleagues studied a relatively small cohort of endurance runners, which is likely to have weakened the statistical power of these findings. Thus, substantiation of this relationship between E_C and relative exercise intensity is warranted within a larger cohort of trained distance runners.

Accurate inter-individual comparisons of RE can only be made if this measurement is independent of potential confounding variables. It has long been established that a positive relationship exists between body mass (BM) and absolute O_C measures of RE (Morgan and Daniels 1994). To remove the influence of BM on O_C it has often been expressed as a ratio of BM i.e. $VO_2 \cdot kg^{-1}$ (Morgan and Daniels 1994) under the assumption that a proportional linear relationship exists between these variables. However, some authors have suggested a negative relationship exists between BM and ratio scaled O_C (Pate et al. 1992; Bourdin and Pastene 1993), which would indicate that ratio scaled O_C overcompensates for the influence of BM. Measurements of absolute oxygen uptake during running suggest that O_C might be more appropriately scaled to a power function exponent of BM that is <1 in endurance trained individuals, specifically $BM^{\cdot -0.75}$ (Bergh et al. 1991). However, the aforementioned study employed a mixed cohort of endurance trained individuals from several exercise modalities. The relationship between BM and measures of RE has yet to be examined in a large cohort of competitive distance runners, and therefore the appropriate scaling of E_C relative to BM in this population remains to be elucidated.

Therefore, the primary aim of the current investigation was to assess the validity of O_C as a measure of RE in comparison to the underlying E_C, and consider whether these measurements are influenced by running speed. It was hypothesised that, although E_C would increase with increments in running speed, measurements of O_C would be insensitive to changes in running speed. The secondary aim was to determine the most valid method of accounting for BM in the measurement of RE in a large cohort of highly trained distance runners.

4.2 Materials and methods

4.2.1 Overview

The work was a retrospective analysis of data collected from 172 healthy endurance trained athletes with competitive distances ranging from 800m to the marathon (males, n = 101; females, n = 71; Table 4.1). The following tests were performed after informed consent was obtained as a part of sports science support provision, with procedures approved by the Internal Review Board of English Institute of Sport. Data were collected from two laboratories, with all tests conducted as part of athlete support services between November 2004 and April 2013. Of the participants assessed, 112 (males, n = 65; females, n = 47) were classed as middle distance runners, defined by a primary competitive distance ≤ 3000m (6), with 60 classed as long distance runners (males, n = 36; females, n = 24).Where multiple visits from the same athlete had occurred during the study period, data only from their final visit were included in the analysis. Participants wore appropriate racing ‘flats’ shoes, and laboratory conditions were similar throughout all running assessments (temperature 20.5 ± 1.9 °C, relative humidity 45.9 ± 9.7%).

4.2.2 **Protocol**

Submaximal running assessments

Following a warm-up at a self-selected running speed (typically 10-12 km.hr^{-1} for ~10 min), participants completed a discontinuous submaximal incremental test consisting of six to nine bouts of 3 minutes continuous running, with increments of 1 km·h^{-1} on a motorised treadmill of known speed (HP cosmos Saturn, Traunstein, Germany) interspersed by 30 s rest for blood sampling. As the speeds assessed were typically between 10.5 km·h^{-1} and 18 km·h^{-1}, treadmill gradient was maintained at 1% throughout submaximal assessments in order to reflect the energetic cost of outdoor running (Jones and Doust 1996). The heart rate (HR) response during the warm-up was used to determine a starting speed and provide ~4 speeds prior to lactate turnpoint (LTP). Increments were continued until blood lactate had risen by ~2 mmol·L^{-1} from the previous stage. HR (s610i, Polar, Finland) and pulmonary gas exchange were recorded throughout the test.

Table 4.1. Physiological and anthropometrical characteristics.

	Females (*n* = 71)	**Males** (*n* = 101)
Age (yrs)	23 ± 5	23 ± 6
Body mass (kg)	54.8 ± 4.7*	67.1 ± 7.0
Stature (cm)	169 ± 5*	180 ± 7
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	65.9 ± 6.5*	73.0 ± 6.6
vLTP (km·h^{-1})	15.6 ± 1.3*	17.4 ± 1.4

* denotes a significant difference to males ($P < 0.001$). $\dot{V}O_{2max}$ - maximal oxygen consumption. vLTP – velocity at LTP

Maximal running assessments

$\dot{V}O_{2max}$ was determined by a continuous incremental treadmill running test to volitional exhaustion. After a warm-up, participants initially ran at a speed 2 km·h^{-1} below the final speed of the submaximal test and at a 1% gradient. Each minute, the incline was increased by 1% until volitional exhaustion, typically achieved in 6-8 minutes.

4.2.3 **Measurements**

Anthropometry

Prior to exercise BM was measured using digital scales (Seca 700, Seca, Hamburg, Germany) to the nearest 0.1 kg. Stature was recorded to the nearest 1 cm using a stadiometer (Harpenden Stadiometer, Holtain Limited, UK).

Pulmonary gas exchange

Breath-by-breath gas exchange data were measured with an automated open circuit metabolic cart (Oxycon Pro, Carefusion, San Diego, USA). Participants breathed through a low-dead space mask, with air sampled at 60 ml·min^{-1}. Prior to each test, two point calibrations of the gas sensors were completed, using a known gas mixture (16% O_2, 5% CO_2) and ambient air. Ventilatory volume was calibrated using a 3 L (±0.4%) syringe. Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and RER values were quantified over the final 60 s of each stage of the submaximal protocol.

Blood lactate

A 20µl capillary blood sample was taken from the earlobe for analysis of blood lactate ($[La]_b$) (Biosen C-line, EKF diagnostics, Germany). The LTP was identified via the modified Dmax method. Briefly, LTP was quantified as the point on the third order polynomial curve fitted to the speed-lactate relationship that generated the greatest perpendicular distance to the straight line formed between the first stage preceding an increase in $[La]_b$ greater than 0.4 mmol.L^{-1} (lactate threshold) and the final stage (Bishop et al. 1998). Based on this value, the four stages prior to LTP were identified for each participant as LTP-4, LTP-3, LTP-2 and LTP-1. Measurements for all 4 stages below LTP were not present for 9 males and 12 females, therefore these participants were excluded from the analysis of running speed vs RE.

Calculation of running economy

The average of breath by breath $\dot{V}O_2$ and $\dot{V}CO_2$ during the final minute of each submaximal stage were used to calculate O_C and E_C. Updated nonprotein respiratory quotient equations (Péronnet and Massicotte 1991) were used to estimate substrate utilisation ($g \cdot min^{-1}$) during the monitored period. The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolised substrates during moderate to high intensity exercise (Jeukendrup and Wallis 2005). Absolute E_C was quantified as the sum of these values, expressed in $kcal \cdot km^{-1}$. The $\dot{V}O_2$ during the final minute of each submaximal stage was used to determine absolute O_C, expressed in $L \cdot km^{-1}$. From previous work in our laboratory, the typical error of measurement was ~3% for both O_C and E_C (Chapter 3).

4.2.4 **Statistical analyses**

The relationships between absolute E_C (averaged over the 3 speeds prior to LTP) and BM were fitted using both a power function, assuming a log linear model to estimate the parameters (i.e. $E_C = a(BM)^b$), and linear models (i.e. $E_C = a(BM) + b$). For power exponents (b), 95% confidence intervals (CI) were calculated. To compare the strength of fit between models, the coefficient of determination and root mean squared errors (RMSE) were calculated. The appropriateness of each model was then assessed using Pearson's product-moment correlation coefficient. If the model has been successful in accounting for BM, the correlation between BM and the assessed variable scaled appropriately to BM should approach zero (Tanner 1949). This analysis was repeated with O_C to compare with previous investigations. Normal distributions of O_C and E_C were assessed via Shapiro-wilk tests prior to comparisons between speeds. Differences in participant characteristics between males and females were assessed via independent samples t-tests. Differences in E_C, O_C and RER between males and females for the 4 speeds prior to LTP were assessed with two-way ANOVA (speed; sex) with mixed measures. One way ANOVA with repeated measures was conducted to assess differences in E_C or O_C across the 4 speeds prior to lactate threshold. Post hoc analysis with Bonferoni adjustment was used to identify where any significant differences occurred. Data are presented as mean ± standard deviations, with significant differences accepted at $P < 0.05$.

4.3 Results

4.3.1 Participant Characteristics

Participant characteristics are shown in Table 4.1. The well trained status of the participants was emphasised by the high $\dot{V}O_{2max}$ and vLTP values for both males and females. The mean of the four stages prior to vLTP were 12.4 – 15.4 km·h^{-1} for females and 13.8 – 16.8 km·h^{-1} for males.

4.3.2 Allometric modelling

Plots of BM against E_C (Figure 4.1) and O_C (Figure 4.2) were fitted with both power and linear functions. The results of the regression analyses with a power function fit between absolute E_C and BM revealed exponents close to unity (males, b = 0.90, CI 0.75-1.05; females, b =0.88, CI 0.66-1.10), and for O_C (males, b = 0.93, CI 0.79-1.06; females, b = 0.95, CI 0.73-1.16). Similar, but marginally higher, R^2 and lower RMSE values were observed for linear ratio scaling compared to power functions for both O_C an E_C (Table 4.2). The appropriateness of the linear model was confirmed by the absence of any relationship when BM was re-plotted against ratio scaled E_C (Kcal·kg^{-1}·km^{-1}) and O_C (mL·kg^{-1}·km^{-1}) for both males (R^2 = 0.017, P = 0.19; R^2 = 0.011, P = 0.30; respectively) and females (R^2 = 0.012, P = 0.36; R^2 = 0.001, P = 0.77; respectively). Consequently, relative expressions of E_C and O_C were scaled to BM^{-1} in all further analysis.

4.3.3 Running speed

No interaction effect was evident between speed and sex for E_C, O_C, and RER, thus both cohorts were combined to analyse the influence of speed on these parameters. ANOVA revealed increases in RER with increments in running speed (P < 0.001; Figure 4.3). Increases in E_C were also observed with increments in running speed (ANOVA, P < 0.001; Figure. 4.3). No differences in O_C were seen across the 4 monitored speeds (ANOVA, P = 0.54).

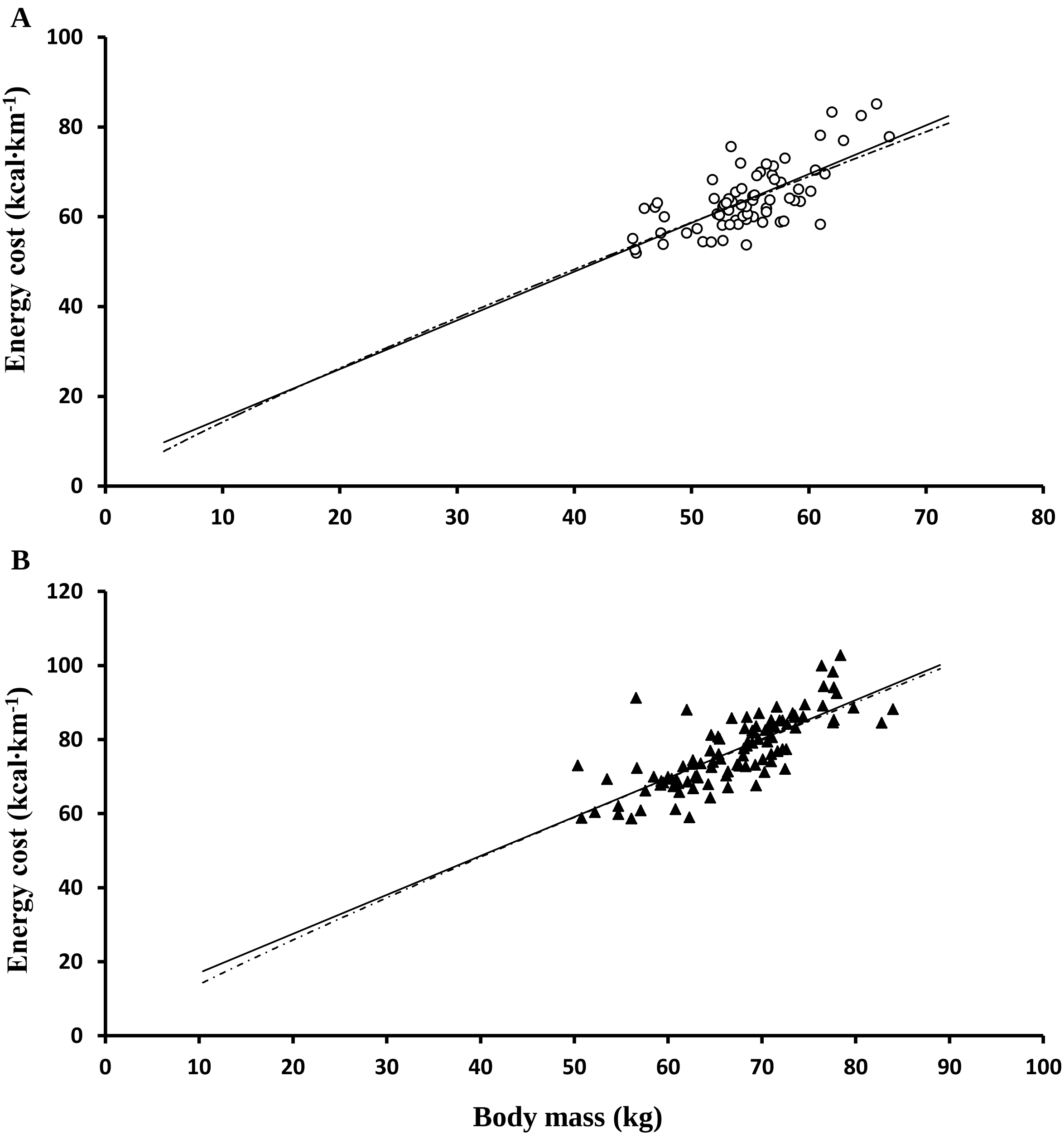

Figure 4.1. Absolute energy cost vs body mass. **A.** Females (n = 71) fitted with linear (solid line; y = 1.087x + 4.323) and power functions (dashed line; y = 1.888x0.879). **B.** Males (n = 101) fitted with linear (solid line; y = 1.052x + 6.506) and power functions (dashed line; y = 1.746x0.900).

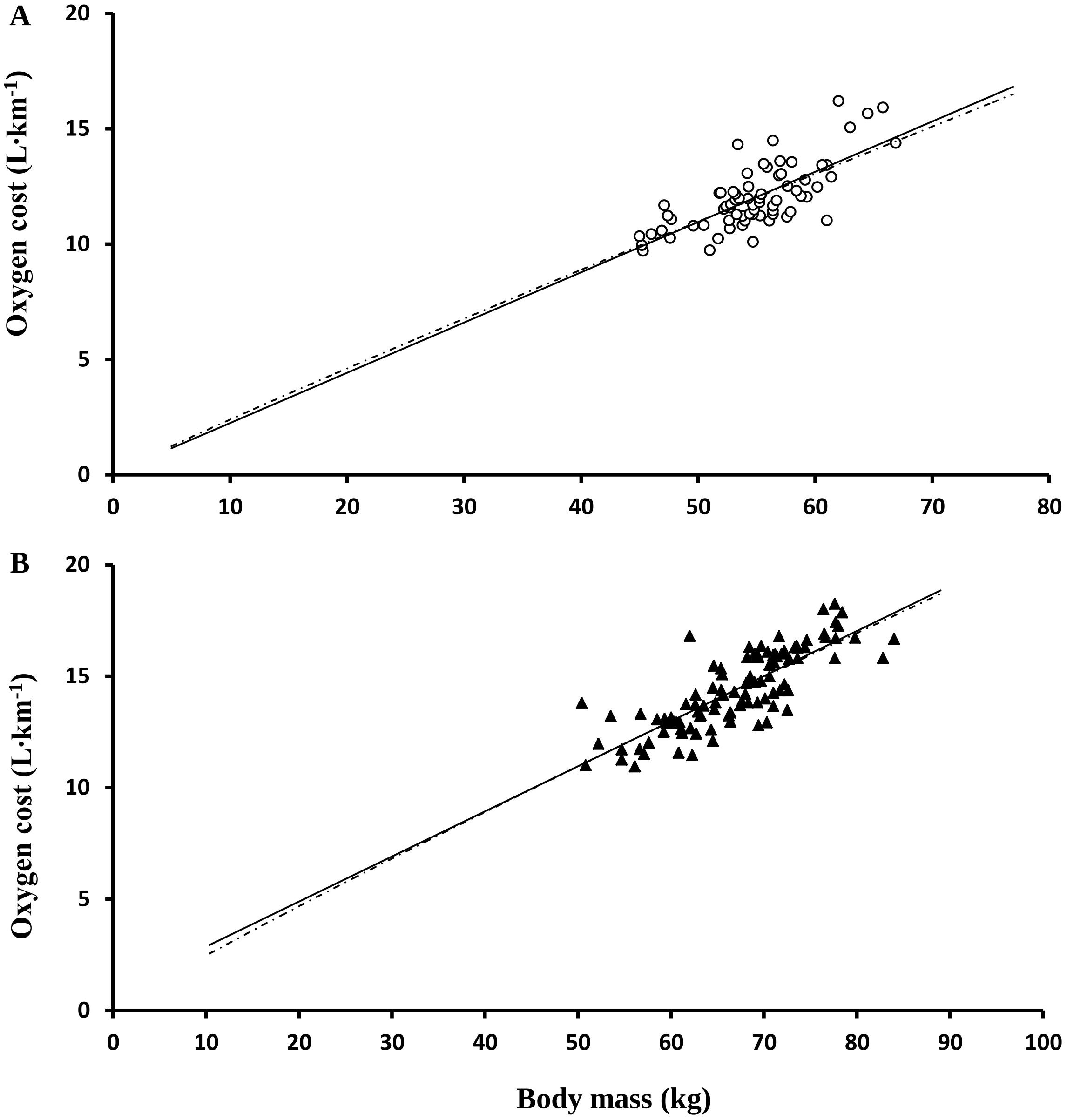

Figure 4.2. Absolute oxygen cost vs body mass. **A**. Females (n = 71) fitted with Linear (solid line; y = 0.218x + 0.063) and power functions (dashed line; y = 0.271x0.946). **B**. Males (n = 101) fitted with Linear (solid line; y = 0.202x + 0.841) and power functions (dashed line; y = 0.290x0.928).

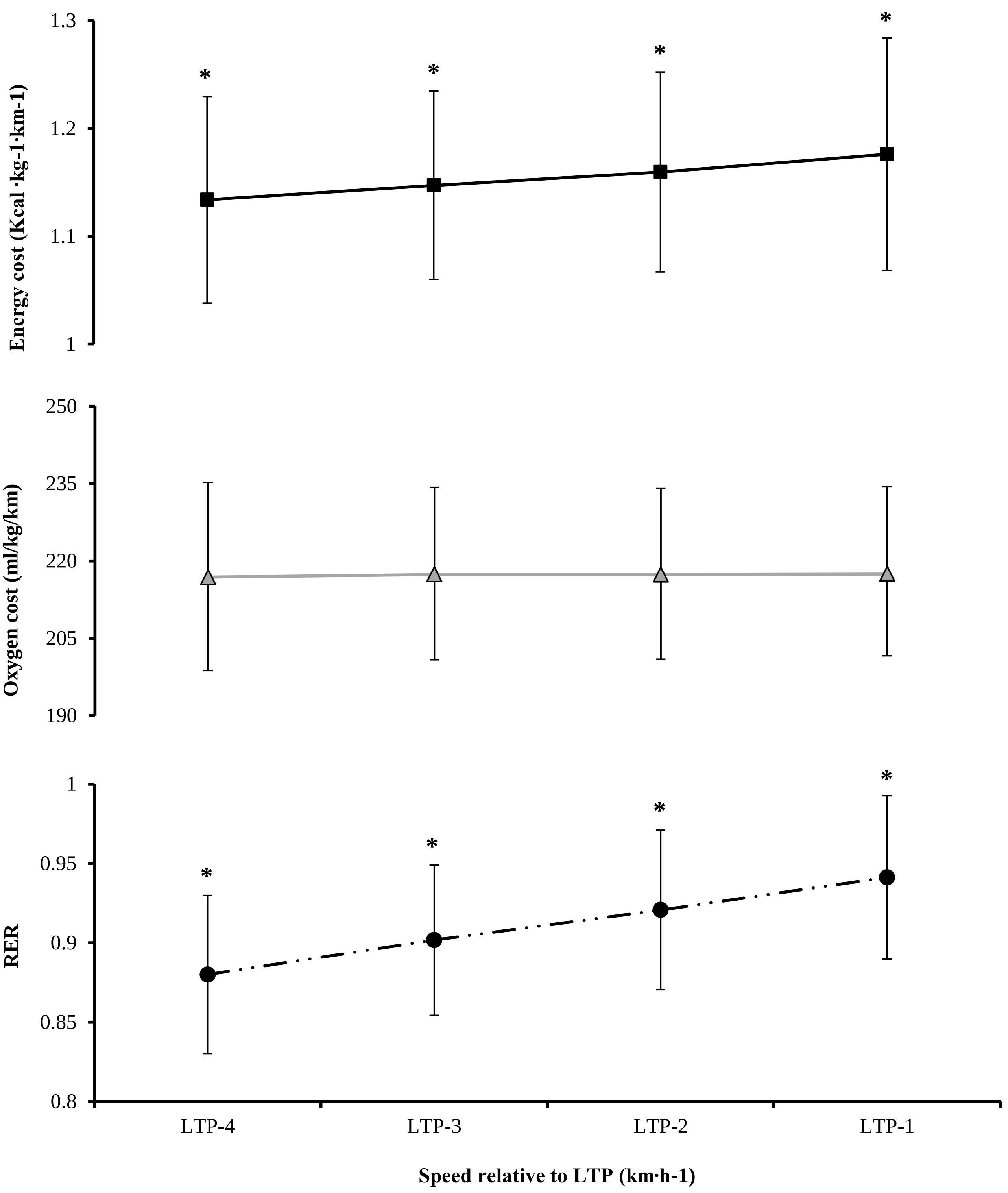

Figure 4.3. Physiological measures at the four speeds prior to lactate turnpoint (LTP; n = 151). * denotes a significant difference from all other speeds (ANOVA with Bonferroni *post hoc* adjustments; P < 0.001).

Table 4.2. The coefficient of determination (R^2) and root mean square error (RMSE) from linear and power scaling between body mass and both energy cost and oxygen cost

Variable	Sex	R^2		RMSE	
		Linear	*Power*	*Linear*	*Power*
Energy cost ($kcal \cdot km^{-1}$)	Males	0.59	0.59	6.15	7.55
	Females	0.50	0.48	5.13	7.11
Oxygen cost ($L \cdot km^{-1}$)	Males	0.66	0.65	1.02	1.66
	Females	0.53	0.53	0.96	1.27

4.4 Discussion

The primary aim of the present study was to investigate the validity of O_C as a quantification of RE by comparing this variable to the underlying E_C of running. A disparity was evident between the changes in O_C and E_C as running speed increased, with significant increases in E_C but no change in O_C, which appeared to be explained by a progressive shift towards carbohydrate metabolism. A further finding was that linear ratio scaling, rather than a power function, was the most appropriate way of accounting for BM when using both measures of RE.

In accordance with previous findings (Fletcher et al. 2009), as running speed progressed towards the vLTP, elevations in E_C were apparent for each increment in running speed; increasing by 3.7% across the 4 speeds assessed, whilst O_C remained consistent; supporting the premise that O_C is independent of running speed (Margaria et al. 1963; Hagberg and Coyle 1984; di Prampero et al. 2009; Fletcher et al. 2009). It is therefore clear that a discrepancy exists between these two variables. Fundamentally, the validity of a given variable can be viewed as the extent to which the data represents what it is intended to measure (Newman and Benz 1998). Given that E_C provides the actual indirect assessment of the underlying energy turnover during running, the differing response of E_C and O_C with running speed questions the validity of O_C as a measure of RE.

The inability of O_C to account for variations in substrate metabolism would appear to explain the discrepancy with E_C. It is well established that RER increases with increments in exercise intensity (Saunders et al. 2004a; Fletcher et al. 2009). Indeed, RER in the present investigation increased from 0.88 to 0.94 across the 4 monitored speeds below LTP, reflecting a shift towards greater utilisation of carbohydrates to fuel energy turnover (Brooks and Mercier 1994). As carbohydrates have a greater energy equivalent per mole of O_2 compared to lipids (Krogh and Lindhard 1920), the increase in carbohydrate metabolism appears to offset the greater energy required at higher speeds, resulting in a stable O_C. As the RER is inherent in the calculation of E_C, it is not influenced by changes in substrate metabolism, enabling the identification of the true relationship of RE and running speed. However, the mechanisms underpinning the association between E_C and running speed remain unclear. Studies utilising rodent models (Barclay et al. 2010) and humans (Katz et al. 1986; Coyle et al. 1992; Hunter et al. 2001) suggest a greater efficiency in type I fibres when compared to type II fibres. The elevated E_C might therefore reflect the increased recruitment of comparatively inefficient type II muscle fibres at higher work rates (Hunter et al. 2001). This could be a consequence of the increasing work rate per se, that requires the recruitment of additional motor units. Furthermore, the changing mechanics of running at higher speeds with greater joint angular velocities and reductions in ground contact times (Chapman et al. 2012), which both require greater rates of force development, might also promote recruitment of type II motor units. Therefore, as alterations in E_C appear to be metabolically driven, it is proposed that future assessments should be conducted at a uniform running intensity relative to vLTP.

The confounding influence of substrate utilisation on O_C might also compromise the interpretation of inter-individual differences, and intra-individual changes, in RE. Notable inter-individual variability in substrate utilisation during exercise has been observed in trained athletes (Bosch 1993; Goedecke et al. 2000). In addition, a greater utilisation of lipids at a given exercise intensity is apparent following endurance training (Gollnick 1985), which might inflate O_C despite no differences in E_C, and potentially be erroneously interpreted as detrimental to performance. Whereas, for prolonged events, an increased utilisation of lipids might benefit performance through enhanced glycogen sparing (Costill et al. 1973; Holloszy and Coyle 1984). Consequently, the inability of O_C to account for variations in substrate utilisation compromises the validity, and subsequent interpretation, of this commonly employed measure of RE. Whilst is it clear that O_C is a critical determinant of endurance running performance (Conley and Krahenbuhl 1980; Ingham et al. 2008), it is proposed that as O_C represents both E_C and substrate utilisation, E_C would provide a more appropriate expression of RE.

The accurate comparison of RE between individuals requires an expression that is independent of the confounding influence of BM. In this study linear ratio scaling had marginally higher R^2 values but lower RMSE than power function scaling, for both E_C and O_C, and therefore appeared to be the most appropriate method to remove the influence of BM on RE in endurance runners. Our findings support recent observations demonstrating ratio scaled RE measurements to be independent of BM (Taboga et al. 2012). In contrast, previous investigations of heterogeneous cohorts of trained athletes have proposed measures of submaximal oxygen uptake to be proportional to $BM^{-0.75}$ (Bergh et al. 1991) and $BM^{-0.69}$ (Markovic et al. 2007). However, unlike the homogenous cohort of endurance runners in the current study, these investigations included athletes from various sporting disciplines as opposed to our cohort from a single discipline (running). Our findings hence demonstrate the necessity to evaluate the appropriate scaling factor for a given population, which might be sensitive to the body composition of the cohort. Given the better fit of the linear model, the comparative simplicity of its calculation, and the wide spread use of this exponent in the literature, the expression of E_C relative to BM^{-1} would appear preferential. It is therefore proposed that measures of RE in highly trained endurance runners should be expressed relative to BM to accurately account for variations in BM.

In conclusion, our data indicate that O_C does not provide a valid index of the underlying E_C of running. Though E_C increased with increments in running speed, O_C is insensitive to such changes, likely because it does not account for variations in substrate utilisation. Moreover, expression of E_C relative to BM^{-1} was found to be the most appropriate method to remove influence of BM on this variable. It is therefore proposed that E_C should be employed as the primary measure of RE, scaled appropriately to BM^{-1}.

CHAPTER V

The use of up-hill and down-hill running as a diagnostic tool for running economy

5.1 Introduction

Running economy (RE), defined as the energy cost to cover a given distance, is a primary physiological determinant of endurance running performance (di Prampero 2003; Ingham et al. 2008). Runners with a superior running economy expend less energy to sustain a given running velocity, and consequently incur a lower metabolic cost. Therefore, modest enhancements in RE are considered to be of significant benefit to performance (Cavanagh 1989). However, few training methods have been shown to enhance RE (Saunders et al. 2004d; Foster and Lucia 2007), potentially restricted by the inability to identify the principal limiting factor of RE. As an athlete's RE could be viewed as a composite of both mechanical and metabolic factors, diagnosis of specific mechanical or metabolic inefficiencies in an athlete could facilitate the prescription of more effective training interventions to enhance RE.

Surface gradient is known to influence the energetic cost of running (E_C) at a given speed (Margaria et al. 1963; Minetti et al. 2002), with running uphill incurring a greater E_C and downhill a lesser E_C when compared to running on the flat. When running on positive gradients, the body's centre of mass (COM) is lifted during each stride cycle primarily through metabolically expensive concentric contractions, resulting in greater physiological work (Snyder et al. 2012). In addition the lower vertical velocity on landing whilst running uphill (Gottschall and Kram 2005; Neves et al. 2014) might reduce the opportunity for elastic energy storage and re-utilisation (Snyder et al. 2012), and thus also elevate the E_C. The E_C of running uphill, in comparison to running on the flat, would seem to be more dependent on the metabolic efficiency of the athlete, with metabolically inefficient athletes likely to incur a greater increase in E_C.

Conversely, during downhill running there is both a reduced requirement for positive work (Snyder et al. 2012) as well as a higher vertical velocity on landing (Yokozawa et al. 2005; Gottschall and Kram 2005; Neves et al. 2014) that might give more opportunity for elastic energy storage and re-utilisation. Consequently, running downhill might shift the emphasis away from metabolic efficiency to mechanical efficiency and the ability to store and re-utilise gravitational potential energy (Snyder et al. 2012). If this were the case running downhill, compared to flat running, may have larger reduction in E_C for mechanically efficient athletes.

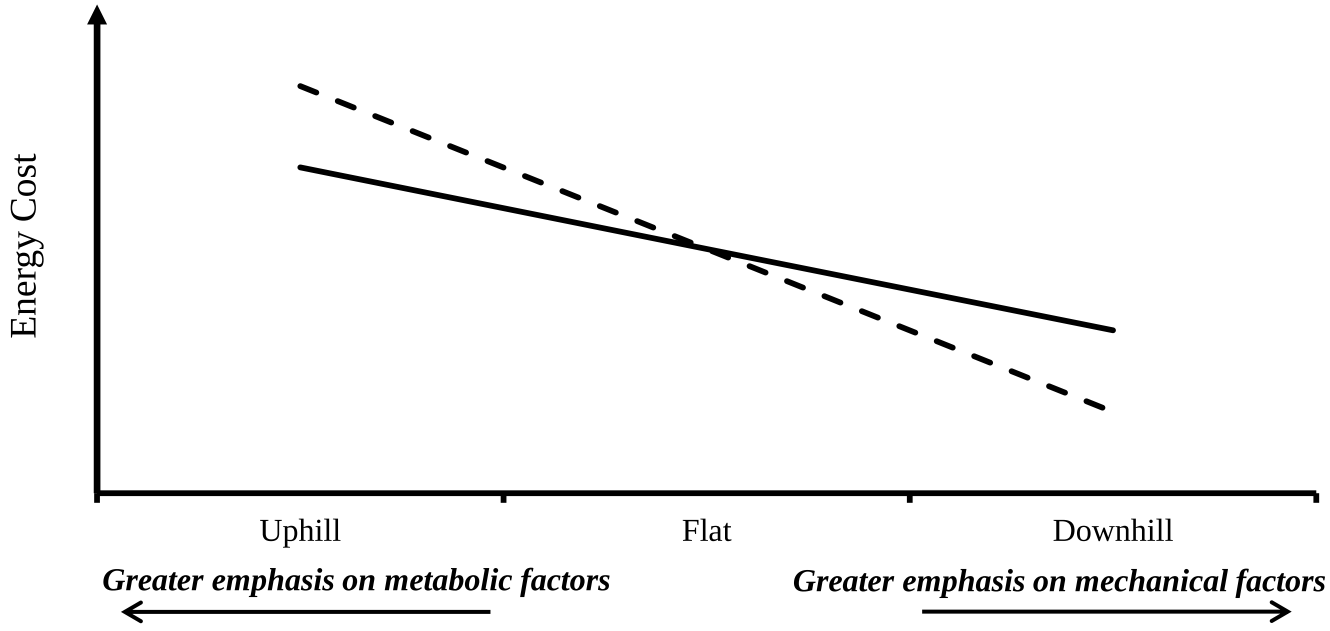

Figure 5.1. Hypothesised variable responses of energy cost to running at different gradients. Two hypothetical athletes are shown with identical running economy during flat running, one with high mechanical efficiency (solid line) and one with high metabolic efficiency (dashed line).

Based on this rationale, runners with high metabolic efficiency would display smaller increases in E_C as gradient increased (i.e. from downhill to flat to uphill), whereas runners with high mechanical efficiency would exhibit larger decreases in E_C as gradient decreased (i.e. from uphill to flat to downhill). In which case the E_C-gradient relationship may vary between runners, being steeper for the most mechanically efficient runners and less steep for the most metabolically efficient runners with other athletes scattered in between (Figure 5.1). We therefore hypothesised that the response to uphill and downhill running might be highly variable between runners. Furthermore, if this were the case then uphill and downhill running may provide a useful diagnostic tool for understanding the determinants and limiting factors to each runner's economy and ultimately facilitate specific interventions to enhance RE. The aim of the current investigation was to evaluate the E_C profiles of trained distance runners across the 3 gradients and assess the variability in these responses.

5.2 Materials and methods

5.2.1 Participants

Thirty healthy trained male distance runners were recruited for this study, however due to inclusion criteria imposed in data analysis (detailed below), 8 participants were subsequently excluded. This investigation therefore represents data from twenty two male distance runners (Age: 28 ± 8 years; stature: 179 ± 5 cm; body mass: 68.5 ± 5.5 kg; $\dot{V}O_{2max}$: 71.8 ± 5.2 $mL \cdot kg^{-1} \cdot min^{-1}$). Participants' best performance times over the last two seasons were 115 ± 6% of the current British record as of January 2014 in their specialist event from 800m up to the marathon. All participants were treadmill habituated, and provided written informed consent prior to participating in this study.

5.2.2 Overview

Participants attended the laboratory on two separate occasions. During the first visit, participants completed a submaximal downhill running assessment followed by a maximal running assessment, with ~15 minutes of rest in between. During the second visit, participants completed the main trial that measured the energy cost of submaximal running at three velocities all performed on three different gradients (flat 0%, uphill +5%, and downhill -5%) i.e. 9 conditions. Gradients were selected to maximise the difference in E_C between conditions, whilst preserving running technique and enabling valid sub LTP assessments of E_C in all conditions. Participants wore appropriate clothing and racing shoes, and laboratory conditions were similar throughout all running assessments (temperature, 18-21°C; relative humidity, 40-50%). Heart rate (s610i, Polar, Finland) and pulmonary gas exchange (detailed below) were monitored throughout all assessments.

5.2.3 Protocol

Submaximal physiology assessment

Following a warm-up (~10 min at 10-12 $km \cdot h^{-1}$), participants completed a discontinuous submaximal incremental test on a motorised treadmill of known belt speeds (HP cosmos Saturn, Traunstein, Germany). This involved six to nine stages with 3 minutes of continuous running at each stage, interspersed by 30 s rest periods and increments of 1 $km \cdot h^{-1}$. As the speeds assessed were typically between 10.5 km·h^{-1} and 18 km·h^{-1}, treadmill gradient was maintained at 1% throughout submaximal assessments in order to reflect the energetic cost of outdoor running (Jones and Doust 1996). Recent performance times of participants were used to determine an appropriate starting speed to provide ~4 speeds prior to lactate turnpoint (LTP). Increments were continued until blood lactate concentration had risen exponentially, typically defined as an increase in blood lactate of ~2 mmol·L^{-1} from the previous stage. The LTP was identified to the nearest km·h^{-1} from blood lactate concentration vs. speed relationship.

Maximal running assessments

The maximal rate of oxygen uptake ($\dot{V}O_{2max}$) was determined by a continuous incremental treadmill running ramp test to volitional exhaustion. After a warm-up, participants initially ran at a speed 2 km·h^{-1} below the final speed of the submaximal test and at a 1% gradient. Each minute, the incline was increased by 1% until volitional exhaustion, reached typically in 6-8 minutes.

Main Trial – Energy cost of running at different gradients

On the second visit, following 15 minutes of standing rest, participants were required to complete nine 4 minute running stages, interspersed with 1 minute of rest. For the first 3 stages, running velocity was set at 70% of the velocity at lactate turnpoint (vLTP) determined from the prior assessment, with a surface gradient of 0% (flat), +5% (uphill; 2.9°) and -5% (downhill; -2.9°) respectively. This process was then repeated at running velocities of 75 and 80% of vLTP. Data for all biomechanical and physiological parameters (detailed below) were collected in the final 60s of each running stage.

5.2.4 **Measurements**

Anthropometry

Prior to exercise on laboratory visits, body mass was measured using digital scales (Seca 700, Seca, Hamburg, Germany) to the nearest 0.1 kg. Stature was recorded to the nearest 1 cm using a stadiometer (Harpenden Stadiometer, Holtain Limited, UK).

Blood lactate

During rest periods in the submaximal running assessment, a 20µL capillary blood sample was taken from the earlobe for analysis of blood lactate ([La]b) (Biosen C-line, EKF diagnostics, Germany). LTP was defined as the running speed above which blood lactate concentration increased by >1.0 $\text{mmol}\cdot\text{L}^{-1}$ from the previous stage (Thoden 1991).

Pulmonary gas exchange

Breath-by-breath gas exchange data was quantified via an automated open circuit metabolic cart (Oxycon Pro, Carefusion, San Diego, USA). Participants breathed through a low dead-space mask, with air sampled at 60 $\text{mL}\cdot\text{min}^{-1}$. Prior to each test, two point calibrations of both gas sensors were completed, using a known gas mixture (16% O_2, 5% CO_2) and ambient air. Ventilatory volume was calibrated using a 3 L (± 0.4%) syringe. The final 60 s of each stage were used to quantify oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and RER. The greatest continuous sample of $\dot{V}O_2$ averaged over 30s defined $\dot{V}O_{2max}$. Resting $\dot{V}O_2$ was defined as the average $\dot{V}O_2$ assessed over the final 10 minutes of standing rest.

Calculation of running economy

$\dot{V}O_2$ and $\dot{V}CO_2$ during the final minute of each stage of the main trial, less resting values, were used to calculate net E_C. Updated nonprotein respiratory quotient equations (Péronnet and Massicotte 1991) were used to estimate substrate utilisation ($\text{g}\cdot\text{min}^{-1}$) during the monitored period. For eight athletes an RER > 1 was recorded during uphill running, thus violating the assumptions required to derive substrate utilisation and indicating anaerobic metabolism that invalidates the calculation of E_C. Consequently, these athletes were excluded from further analysis. The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolised substrates during moderate intensity exercise (Jeukendrup and Wallis 2005). E_C was quantified as the sum of these values, expressed as in absolute terms ($\text{kcal}\cdot\text{min}^{-1}$) and relative terms ($\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$). $\dot{V}O_2$ during the final minute of each stage, less resting values, were used to determine oxygen cost ($O_{C;}$ $\text{mL}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) for comparative purposes.

Biomechanical parameters

A photoelectric cell system (Optojump, Microgate, Bolzano, Italy) was used to measure ground contact time, flight time, stride length and stride frequency over the final 60s of each running stage during the main trial. The system consisted of two parallel units (a transmitter and a receiver), set on opposing sides of a 2 m section of the treadmill belt. The Optojump system was positioned 0.3 cm above the plane of the treadmill belt and each transmitter contained 96 equidistant LEDs per meter, recording at 1 kHz. All parameters were quantified using the Optojump Next software (v 1.9.9.0). Data were filtered to remove erroneous values >2 standard deviations away from the mean. Vertical oscillation was assessed using a high speed (240 Hz) camera (Casio Exilim EX-ZR 100, Casio Computer Co. Ltd., Tokyo, Japan) situated 1m behind the treadmill at a height of 2m, with a reflective marker placed on the participants' 3rd lumbar vertebrae as an approximate measure of the displacement of the COM. Recordings were digitised (Quantic Biomechanics v26, Quitic consultancy LTD, UK), with vertical oscillation defined as the greatest vertical displacement of the COM during a complete step, and averaged over 10 continuous steps. Oscillation of the COM was expressed relative to leg length, calculated as the distance between the greater trochanter and the lateral malleolus on the right leg.

5.2.5 Statistical analyses

Data are presented as mean ± SD for all dependant variables. Data analysis was conducted using SPSS for windows (v21; IBM Corporation, Armonk, NY). Normal distribution of the dependant variables were confirmed via Shaprio-wilk tests, and the variance were found to be homogenous across the 3 gradients. Pearson's product-moment correlation coefficient between measures of E_C (Kcal·kg^{-1}·km^{-1}; averaged over the 4 stages prior to LTP the submaximal assessment) and body mass were used to assess the appropriateness of linear modelling to remove the influence of body mass in accordance with chapter 3. One-way ANOVA with repeated measures were used to assess any differences in RE and biomechanical variables between surface gradients. Where differences were found, post-hoc analyses with Bonferroni adjustments were conducted. Partial correlations, and associated 95% confidence intervals (CI) were used to assess relationships between E_C (average of the 3 speeds; Kcal.min^{-1}) during flat, uphill and downhill running whilst controlling for body mass and running speed to avoid spurious correlations created by correlating two variables with common divisors (Pearson 1986). Partial correlations and associated 95% confidence intervals (CI) were also used to assess relationships between E_C during flat running and both the absolute change in RE from flat running to uphill running (uphill E_C – flat $E_{C;}$ ΔUp) and downhill running (downhill E_C – flat E_C; ΔDown), in addition to the relationship between ΔUp and ΔDown. Between athlete coefficient of variations were calculated for ΔUp and ΔDown to assess the variability of the responses to different gradients. Effect size descriptors (trivial 0.0 – 0.1, small 0.1 – 0.3, moderate 0.3 - 0.5, large 0.5 - 0.7, very large 0.7 – 0.9, nearly perfect 0.9 - 1, perfect 1) were used to infer correlation magnitude (Hopkins et al. 2009), with significance accepted at $P \leq 0.05$.

5.3 **Results**

5.3.1 **Biomechanical changes with the different gradients**

The running speeds associated with 70, 75 and 80% vLTP were 11.7 ± 0.6, 12.5 ± 0.7 and 13.4 ± 0.7 $km \cdot h^{-1}$, respectively. Stride parameters (stride length, frequency, ground contact time and flight time) were not available for 3 athletes due to limitations with equipment. Averaged over the 3 speeds, uphill running involved a shorter stride, a shorter flight time and an increased stride frequency, as well as less vertical oscillation compared to the flat and downhill conditions (Table 5.1). This pattern was repeated when comparing the flat to the downhill condition. No differences were noted between ground contact times between conditions ($P > 0.05$).

Table 5.1. Gait characteristics during flat, uphill and downhill running.

Note: * denotes significant difference to flat ($P < 0.05$); † denotes significant difference to downhill ($P < 0.005$)

	Surface gradient		
	Uphill	**Flat**	**Downhill**
Ground contact time (s)	.239 ± .015	.238 ± .015	.239 ± .018
Stride length (m)	2.46 ± 0.16*†	2.48 ± 0.21†	2.51 ± 0.16
Stride frequency (Strides.min^{-1})	169 ± 7*†	167 ± 7†	165 ± 7
Flight time (s)	.119 ± .021*†	.123 ± .019†	.129 ± .026
Vertical Oscillation (% leg length)	11.6 ± 1.3*†	12.3 ± 1.46†	12.7 ± 1.6

5.3.2 **Running economy**

Pearson's correlations confirmed the appropriateness of linear modelling to remove the influence of body mass on E_C (R^2=0.11; P=0.14). The absolute and relative E_C during uphill, flat and downhill running are displayed in Figure 5.2. There were differences in E_C between gradients (ANOVA, $P < 0.001$), with E_C greatest during uphill running (1.28 ± 0.07 $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$), lower during flat running (0.97 ± 0.08 $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) and lower still during downhill running (0.80 ± 0.08 $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$; Figure 5.2a). The relative O_C during uphill, flat and downhill running was 241.7 ± 14.2 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$, 188.1 ± 15.0 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$ and 155.6 ± 14.4 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$, respectively. Compared to flat running, E_C was +31.9 ± 4.4% during uphill running (ΔUp) and -17.4 ± 2.6% during downhill running (ΔDown), with O_C displaying a similar pattern (ΔUp +28.5%, ΔDown -17.3%). The between athlete coefficient of variations for absolute E_C ΔUp and ΔDown were 10.4% for and 14.0%, respectively.

Partial correlation analysis, whilst controlling for body mass and speed, revealed no association between ΔUp and ΔDown ($r = 0.10$; $P = 0.69$; CI -0.38 – 0.54), indicating that there were not consistent responses to these two changes in gradient. Moreover, partial correlations revealed very large positive associations between the E_C of flat and uphill running ($r = 0.85$; $P < 0.001$; CI 0.65 – 0.94) and uphill and downhill running ($r = 0.77$; $P < 0.001$; CI 0.49 – 0.91), with a nearly perfect association between E_C of flat and downhill running ($r = 0.9$; $P < 0.001$; CI 0.75 – 0.96; Figure 5.3).

5.4 Discussion

The aim of the current investigation was to evaluate the E_C of running on flat, positive and negative gradients in trained distance runners. As expected, E_C was highest during uphill running, and lowest during the downhill running. However, a difference was observed in the magnitude of the change in E_C from flat running to uphill or downhill running, with a smaller reduction in E_C running downhill when compared to the increase in E_C of running uphill. This response was consistent across the group, with little between subject variation for the changes in E_C for uphill and downhill compared to flat running. In addition, very strong positive associations were seen between the E_C measured at all three gradients, indicating the different gradients produced similar responses for all the runners and did not strongly discriminate for individual characteristics.

In accordance with previous investigations, the positive and negative gradients resulted in notable alterations in E_C from flat running (Ardigo et al. 1995; Lussiana et al. 2013; Vernillo et al. 2015). Running up a +5% gradient incurred a 32% greater E_C than flat running (ΔUp), which is consistent with previous observations at slower running speeds (Minetti et al. 1994; Lussiana et al. 2013). However, running down the same gradient (-5%) produced a smaller energy saving (ΔDown -17%) supporting data from Vernillo and colleagues (2015), and highlights a disparity between the energy saving of running downhill and the additional energy cost of running uphill. Intuitively, these findings could reflect an inflated energy cost of running uphill beyond the savings achieved running downhill (i.e. a relative inefficiency during uphill running), and / or a restricted energy saving downhill compared to the cost of running uphill (i.e. a relative inefficiency during downhill running). During downhill running, vertical oscillation of the COM was ~10% greater than uphill running. As previous investigations have reported a positive association between vertical oscillation and RE (Williams and Cavanagh 1987a; Halvorsen et al. 2012), it is possible that the greater vertical displacement could offset some of the savings in E_C during downhill running. In addition, though not assessed in the current investigation, the higher work rate during uphill running could increase the recruitment of comparatively inefficient type II muscle fibres (Hunter et al. 2001), further inflating E_C during uphill running. However, further study would be required to confirm these hypotheses.

The current investigation was the first to document the association between ΔUp and ΔDown, in addition to the association between absolute E_C across the three different gradients. It was proposed that increasing the surface gradient, throughout the range down-flat-up, would place more emphasis on metabolic efficiency, and decreasing the gradient, throughout the range up-down-flat, would place more emphasis on mechanical efficiency. If this were the case, ΔUp would be related to ΔDown. Our results demonstrated no association between ΔUp and ΔDown in our cohort of highly trained endurance runners. Moreover, very large associations were evident between E_C during uphill running and both flat ($r = 0.85$) and downhill ($r = 0.77$), in addition to a near perfect association between E_C during flat and downhill running ($r = 0.9$). These large correlations indicate that runners who have the lowest E_C during flat running largely display the lowest E_C when running on shallow positive and negative gradients. Therefore, contrary to our hypotheses, running on shallow positive and negative

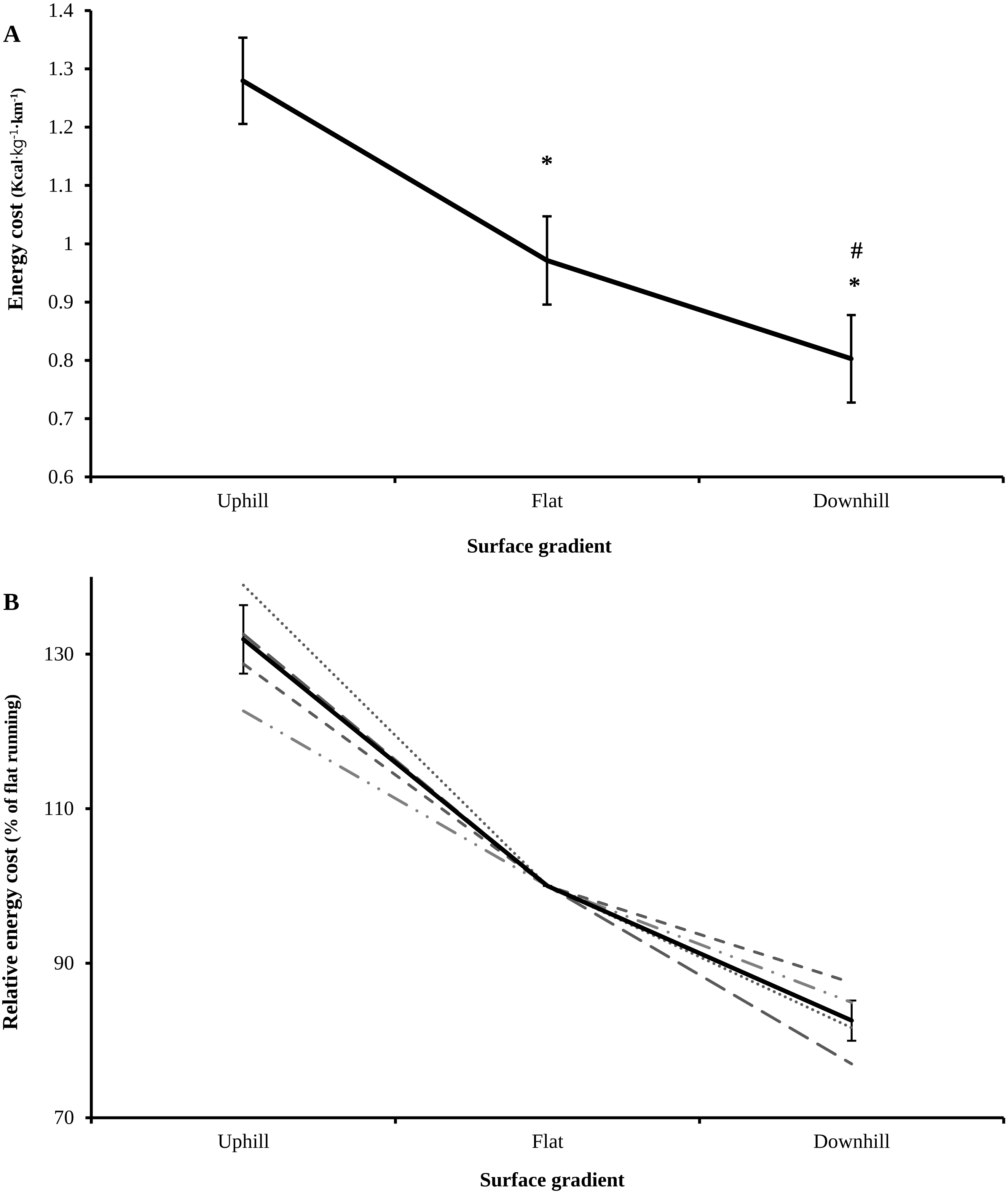

Figure 5.2 The energy cost of uphill, flat and downhill running expressed in **A**. absolute values and **B**. relative to the energy cost of flat running. Individual data is displayed for the four athletes who exhibited the greatest and smallest change during uphill or downhill relative to flat running. * - denotes significant difference to uphill ($P < 0.001$). # - denotes significant difference to flat running ($P < 0.001$).

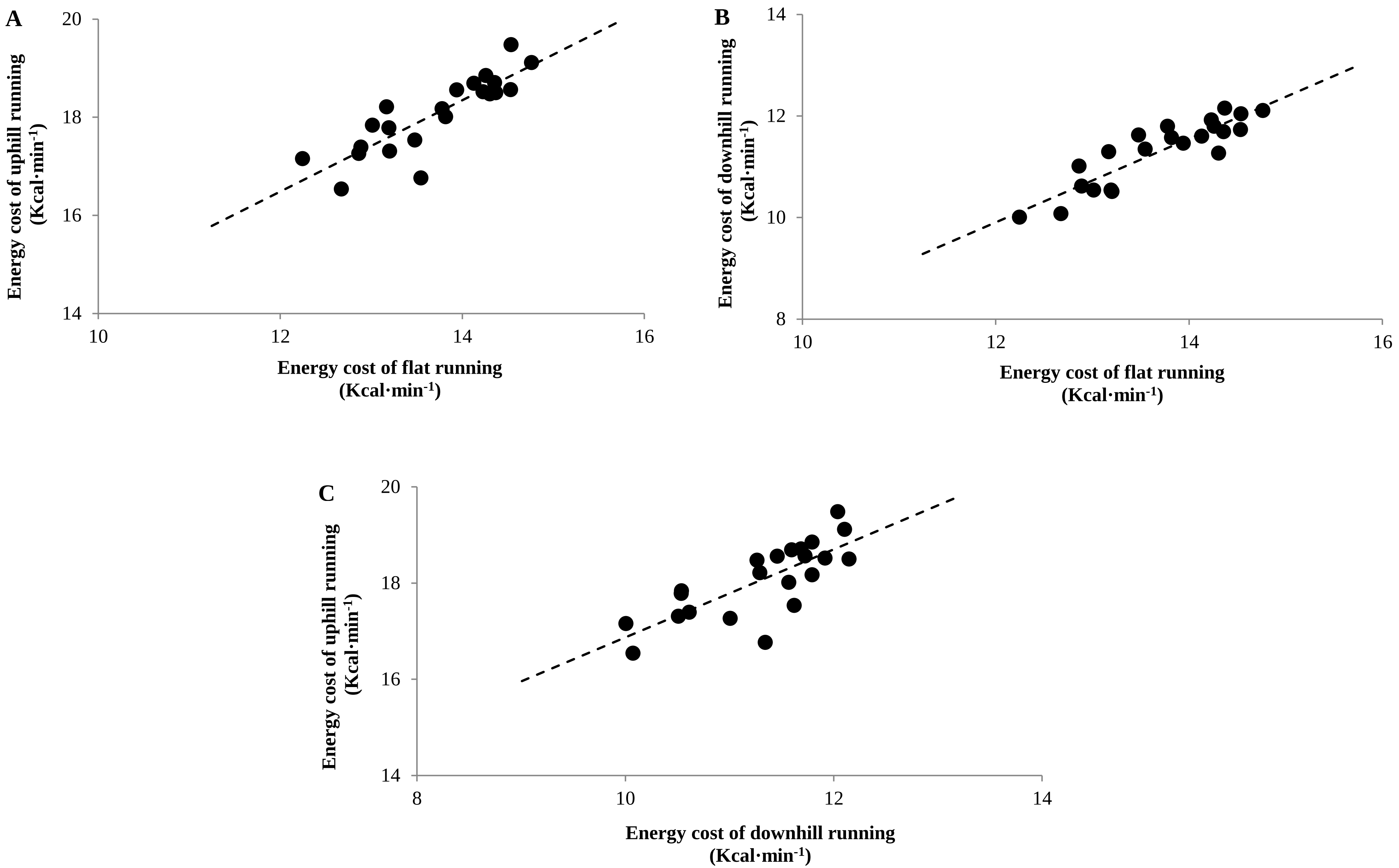

Figure 5.3. Scatter plots of the energy cost (n = 22), adjusted for body mass and speed, during A. uphill running vs flat running (r = 0.85; P < 0.001), B. downhill running vs flat running (r = 0.77; P < 0.001), and C. uphill running vs downhill running (r = 0.9; P < 0.001).

gradients did not produce highly variable E_C profiles for different runners, with the ΔUp being independent from ΔDown.

It is possible that the low variability in the E_C responses could underpin the lack of association between ΔUp and ΔDown. Despite the notable differences in E_C between gradients, the inter-individual variability in the response to different gradients was limited, with between athlete coefficients of variation <15% for both ΔUp and ΔDown. It is possible that the gradients used in this study were insufficient to differentiate between runners, and could be argued that larger changes in E_C elicited by steeper gradients may better discriminate individuals and their limitations to running economy (e.g. mechanical or metabolic factors). However, running gradients steeper than ±5% may preclude the use of meaningful running speeds, as running speed would have to be reduced for the exercise intensity to remain below LTP.

The findings of the current investigation could have direct implications for running performance, specifically the marathon and cross-country events. As the winning margin in the men's marathon is extremely small (0.4% in major summer games over the last 30 years; www.sports-reference.com), effective tactics and pacing strategies of elite runners to maximise performance are of great interest (Erdmann and Lipinska 2013; Angus 2014). Though it has long been established that RE forms a critical determinant of marathon race pace (Sjödin and Svedenhag 1985; Joyner 1991), the implications of uneven terrain on RE, and thus performance, have been overlooked in the scientific literature. If differential responses in RE were evident on different surface gradients, further opportunities to maximise application of energy, and thus pacing, over the course of a race would result. For example, an individual who is highly economical uphill, but uneconomical downhill, could enhance overall race pace by subtly increasing their pace during uphill sections and reducing pace during downhill sections. However, since our findings indicate that those runners who display superior levels of RE during flat running also display superior RE when running uphill and downhill, a runner with superior RE during flat running is likely to benefit equally on both flat and undulating courses. Hence, the current investigation demonstrates that the assessment of RE during flat running largely determines RE on all shallow uphill and downhill gradients.

In conclusion, the current study demonstrated a disparity between the energy saving of running downhill and the additional energy cost of running uphill. However, the between athlete variation in the changes of E_C from flat running during uphill and downhill running were small, with the changes in E_C from flat running to uphill being independent from the changes in E_C from flat to downhill running. These findings suggest that the different gradients produced similar responses for all the runners, with athletes who have the lowest E_C during flat running also likely to display the lowest E_C when running on shallow positive and negative gradients. Therefore, the use of laboratory based uphill and downhill running does not appear to provide a useful diagnostic tool for understanding the contributions and limiting factors to a runner's economy.

CHAPTER VI

The correlation between running economy and maximal oxygen uptake: cross-sectional and longitudinal relationships in highly trained distance runners

6.1 Introduction

Running economy (RE) and maximal oxygen uptake ($\dot{V}O_{2max}$) are two of the primary determinants of endurance running performance (Joyner 1991; Lucía et al. 2002; di Prampero 2003; Ingham et al. 2008). The combination of RE and $\dot{V}O_{2max}$, defined as the velocity at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$), has been found to account for ~94% of the inter-individual variance in running performance over 16.1 km (McLaughlin et al. 2010). Consequently, exceptional values of both RE and $\dot{V}O_{2max}$ are considered requirements for success in elite endurance competitions, and endurance runners strive to improve both variables through training in order to maximise performance. As the margin of success is extremely small in elite distance running, subtle enhancements in either variable could result in substantial performance gains. Therefore, understanding the relationship of RE and $\dot{V}O_{2max}$ both between and within individuals is necessary to understand and optimise performance.

In cohorts of trained (Pate et al. 1992; Fletcher et al. 2009) and elite (Morgan and Daniels 1994) distance runners, it has been suggested that a superior RE, quantified as the submaximal oxygen uptake, is associated with a lower $\dot{V}O_{2max}$. These findings have been used to postulate that superior economy compensates for a lower $\dot{V}O_{2max}$ in some individual to achieve a similar performance level (Morgan and Daniels 1994; Lucía et al. 2002; Santalla et al. 2009). However, these investigations have often been restricted to small sample sizes (<25 participants (Morgan and Daniels 1994; Lucía et al. 2002; Fletcher et al. 2009)), and the validity of their statistical techniques has been questioned due to the expression of both variables relative to body mass (i.e. $mL\cdot kg^{-1}\cdot min^{-1}$); creating a common divisor that is known to produce spurious correlations (Atkinson et al. 2003). Partial correlation analysis would provide an appropriate method to account for the influence of body mass on both variables whilst avoiding statistical artefacts, however this method has yet to be used to examine the relationship between RE and $\dot{V}O_{2max}$. Furthermore, studies have solely employed oxygen cost (O_C) as a measure of RE, rather than the comprehensive measurement of energy cost (E_C).

Thus, whether a genuine association exists between RE and $\dot{V}O_{2max}$ remains unclear from the limited cross-sectional observations to date.

Moreover, the concurrent alterations in RE and $\dot{V}O_{2max}$ that occur in athletes over time with training might further reveal if there is an inherent association between these variables, whilst also informing the optimisation of both variables and thus performance. Previous investigations in well trained athletes have noted enhancements in cycling efficiency following short-term, intensive endurance training, but with no change in $\dot{V}O_{2max}$ evident (Iaia et al. 2009; Hopker et al. 2009; Santalla et al. 2009). In contrast, a recent investigation reported an association between individual changes in cycling efficiency and $\dot{V}O_{2max}$ in response to endurance training and across a competitive season; despite no change in mean group $\dot{V}O_{2max}$ (Hopker et al. 2012). These preliminary findings highlight the significance of this relationship for elite endurance athletes, as enhancements in either RE or $\dot{V}O_{2max}$ might only be achievable at the expense of the other variable. However, this previous investigation was limited to measurements of gross efficiency, with no data presented on movement economy. Moreover, analysis of this longitudinal relationship was restricted to observations in small cohorts of athletes, and with responses to run training yet to be explored.

The primary aim of the current investigation was to explore the cross-sectional relationship between $\dot{V}O_{2max}$ and RE, quantified as E_C (O_C data are also presented for comparative purposes), in a large cohort of highly trained distance runners. The secondary aim was to examine the longitudinal relationship between the changes in $\dot{V}O_{2max}$ and RE occurring in athletes in response to endurance training.

6.2 Materials and methods

6.2.1 Overview

The cross-sectional investigation involved retrospective analysis of data from 168 healthy endurance trained athletes with competitive distances ranging from 800m to the marathon (males, n = 98; females, n = 70), who undertook testing and monitoring as part of their sport science support from the English Institute of Sport. The following tests were performed after written informed consent was obtained as a part of sports science support provision, with procedures approved by the Internal Review Board of English Institute of Sport. Of the participants assessed, 97 (males, n = 57; females, n = 40) were classed as middle distance runners, defined by a primary competitive distance ≤ 3000m (Brandon 1995), with 71 classed as long distance runners (males, n = 41; females, n = 30). During the season following their final visit, athlete's best performance times in their primary competitive distance were 89.1 ± 6.1% and 91.2 ± 4.4% of the current British record for males and females, respectively. Data were collected from two laboratories, with all tests conducted as part of athlete support services between November 2004 and April 2013. Participants provided informed consent prior to physiological assessments, in addition to an athlete agreement providing permission for the use of their data in anonymous retrospective analysis. During each visit to the laboratory, participants completed first submaximal and then maximal running assessments (detailed below). Participants wore appropriate clothing (shorts and a vest or t-shirt) and racing shoes, and laboratory conditions were similar throughout all running assessments (temperature 20.6 ± 1.9 °C, relative humidity 45.9 ± 9.8%). As differences in RE and $\dot{V}O_{2max}$ have been noted between sexes (Daniels and Daniels 1992; Helgerud 1994; Helgerud et al. 2010), males and females were analysed separately for cross sectional analyses.

The longitudinal aspect of the study was based on 54 participants (males, n = 27; females, n = 27) from amongst the larger cohort of 168 runners, that had completed at least one follow up assessment, with a median trial separation of 203 days (range: 37 – 2567 days) in order to assess within-athlete changes in both RE and $\dot{V}O_{2max}$ over time. The number of repeat assessments in the longitudinal analysis varied between participants, with a median of 3 visits per athlete (range: 2 – 10 visits), summating to 182 assessments in total. No evidence is currently available regarding sex differences in the concurrent alterations in RE and $\dot{V}O_{2max}$ in response to habitual endurance training, thus data for males and females were combined for longitudinal analysis.

6.2.2 **Protocol**

Submaximal running assessments

Following a warm-up (~10 min at 10-12 $km \cdot h^{-1}$), participants completed a discontinuous submaximal incremental test consisting of six to nine stages of 3 minutes continuous running, with increments of 1 $km \cdot h^{-1}$ on a motorised treadmill of known belt speeds (HP cosmos Saturn, Traunstein, Germany) interspersed by 30 s rest periods for blood sampling. As the speeds assessed were typically between 10.5 $km \cdot h^{-1}$ and 18 $km \cdot h^{-1}$, treadmill gradient was maintained at 1% throughout submaximal assessments in order to reflect the energetic cost of outdoor running (Jones and Doust 1996). This protocol has been shown to be reliable measures of running economy when quantified as both E_C and O_C (typical error ~3%; (Shaw et al. 2013)). Moreover, the controlled laboratory environment enabled assessments of E_C whilst avoiding the confounding influence of air resistance that is evident during outdoor running as speed increases (Pugh 1970). Recent performance times of participants were used to determine an appropriate starting speed to provide ~4 speeds prior to lactate turnpoint (LTP). Increments were continued until blood lactate concentration had risen exponentially, typically defined as an increase in blood lactate of ~2 mmol·L^{-1} from the previous stage. HR (s610i, Polar, Finland) and pulmonary gas exchange (detailed below) were monitored throughout the test.

Table 6.1. Physiological and anthropometrical characteristics of athletes within the cross sectional and longitudinal investigations.

	Cross sectional		**Longitudinal sub-group**	
	Females (*n* = 70)	***Males*** (*n* = 98)	***Females*** (*n* = 27)	***Males*** (*n* = 27)
Age (yrs)	23 ± 4	23 ± 6	23 ± 5	21 ± 3
Body mass (kg)	55.2 ± 4.7	67.1 ± 7.1	55.4 ± 4.3	66.6 ± 6.0
Stature (cm)	169 ± 5	179 ± 7	168 ± 4	179 ± 6
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	65.2 ± 5.9	73.0 ± 6.3	64.5 ± 4.9	73.6 ± 5.9
vLTP (km·h^{-1})	15.5 ± 1.2	17.2 ± 1.3	15.7 ± 1.2	17.6 ± 1.1
Running economy (kcal·kg^{-1}·km^{-1})	1.15 ± 0.09	1.14 ± 0.09	1.13 ± 0.06	1.13 ± 0.07

$\dot{V}O_{2max}$, maximal oxygen uptake; vLTP, velocity at lactate turnpoint

Maximal running assessments

$\dot{V}O_{2max}$ was determined by a continuous incremental treadmill running ramp test to volitional exhaustion. After a warm-up, participants initially ran at a speed 2 km·h^{-1} below the final speed of the submaximal test and at a 1% gradient. Each minute, the incline was increased by 1% until volitional exhaustion. The test duration was typically 6-8 minutes.

6.2.3 **Measurements**

Anthropometry

Prior to exercise on laboratory visits, body mass was measured using digital scales (Seca 700, Seca, Hamburg, Germany) to the nearest 0.1 kg. Stature was recorded to the nearest 1 cm using a stadiometer (Harpenden Stadiometer, Holtain Limited, UK).

Pulmonary gas exchange

Breath-by-breath gas exchange data were quantified via an automated open circuit metabolic cart (Oxycon Pro, Carefusion, San Diego, USA). Participants breathed through a low dead-space mask, with air sampled at 60 mL·min^{-1}. Prior to each test, two point calibrations of both gas sensors were completed, using a known gas mixture (16% O_2, 5% CO_2) and ambient air. Ventilatory volume was calibrated using a 3 L (±0.4%) syringe. This system has previously been shown to be a valid apparatus for the determination of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) at both low and maximal exercise intensities (Rietjens et al. 2001). As previous data from our laboratory has demonstrated a steady state $\dot{V}O_2$, and $\dot{V}CO_2$ is achieved within the first 2 minutes of each stage for highly trained endurance runners (Shaw et al. 2013), mean values from breath-by-breath measures over the final 60 seconds of each stage were used to quantify $\dot{V}O_2$, carbon dioxide production $\dot{V}CO_2$, and RER.

Blood lactate

A 20µL capillary blood sample was taken from the earlobe for analysis of blood lactate ($[La]_b$) (Biosen C-line, EKF diagnostics, Germany). The LTP was identified via the modified Dmax method (Bishop et al. 1998). LTP was quantified as the point on the third order polynomial curve fitted to the speed-lactate relationship that generated the greatest perpendicular distance to the straight line formed between the stage proceeding an increase in $[La]_b$ greater than 0.4 mmol.L^{-1} (lactate threshold) and the final stage. The four stages prior to LTP were identified for each participant, with an average of these four stages used to quantify O_C and E_C

Calculation of running economy

$\dot{V}O_2$ and $\dot{V}CO_2$ during the final minute of each submaximal stage were used to calculate E_C. Updated nonprotein respiratory quotient equations (Péronnet and Massicotte 1991) were used to estimate substrate utilisation (g·min^{-1}) during the monitored period. The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolised substrates during moderate to high intensity exercise (Jeukendrup and Wallis 2005). E_C was quantified as the sum of these values, expressed in kcal·km^{-1}. $\dot{V}O_2$ during the final minute of each submaximal stage was used to determine oxygen cost (O_C) in mL·km^{-1} to enable comparisons to previous investigations.

6.2.4 **Statistical analyses**

Data are presented as mean ± SD for all dependant variables. Data analysis was conducted using SPSS for windows (v21; IBM Corporation, Armonk, NY). When an individual visited the laboratory for repeated assessments, an average of the assessments was calculated and used for the cross sectional analysis. Pearson's product-moment coefficients were calculated to assess the relationship between body mass and E_C, O_C and $\dot{V}O_{2max}$. As body mass was strongly related to both RE measures (E_C, O_C) and $\dot{V}O_{2max}$, partial correlations controlling for body mass, and associated 95% confidence intervals (CI), were used to assess the relationship between absolute $\dot{V}O_{2max}$ and both E_C and O_C. This method removes the influence of body mass on both RE and $\dot{V}O_{2max}$ whilst avoiding spurious correlations created by correlating two variables with a common divisor (Pearson 1896). For graphical display of these relationships, values of E_C and $\dot{V}O_{2max}$ adjusted for body mass for each individual were calculated based on individual residuals. This involved summating the individual's residual, in comparison to the cohort relationship with body mass (e.g. E_C vs body mass), with the group mean for that variable (Moya-Laraño and Corcobado 2008). For the longitudinal analysis, in order to assess any relationships between the changes over time in absolute $\dot{V}O_{2max}$ and the changes in both E_C and O_C over repeat visits, partial correlation coefficients were calculated using ANCOVA (Bland and Altman 2009); providing a comprehensive model that accounts variations in both body mass and the number of visits per athlete. Cohen's d effect size descriptors (trivial 0.0 – 0.1, small 0.1 – 0.3, moderate 0.3 - 0.5, large 0.5 - 0.7, very large 0.7 – 0.9, nearly perfect 0.9 - 1, perfect 1) were used to infer correlation magnitude (Hopkins et al. 2009). Significance was accepted at $P \leq 0.05$.

6.3 Results

6.3.1 Participant Characteristics

Participant characteristics are shown in Table 6.1. The well trained status of the participants was emphasised by the high $\dot{V}O_{2max}$ and vLTP values for both males and females.

6.3.2 Cross-sectional analysis

Partial correlation analysis controlling for body mass, revealed small positive relationships between E_C and $\dot{V}O_{2max}$ (males r = 0.26, CI 0.07 – 0.44, *P* = 0.009; females r = 0.25, CI 0.02 – 0.46, *P* = 0.036; Figure 6.1), and a moderate positive relationship between O_C and $\dot{V}O_{2max}$ (males r = 0.33, CI 0.14 – 0.50, *P* = 0.001; females r = 0.33, CI 0.10 – 0.52, *P* = 0.006).

Longitudinal analysis

Partial correlation analysis from ANCOVA revealed moderate positive relationships between the changes in E_C and $\dot{V}O_{2max}$ over time (r = 0.35; CI 0.19 – 0.49, *P* < 0.001; Figure 6.2), and changes in O_C and $\dot{V}O_{2max}$ over time (r = 0.44; CI 0.29 – 0.57, *P* < 0.001).

6.4 Discussion

The present investigation explored the cross-sectional and longitudinal relationships between RE and $\dot{V}O_{2max}$ in a large cohort of highly trained distance runners. The major contribution of this study to the field is that only a small to moderate association exists between RE and $\dot{V}O_{2max}$ (R^2 ~ 12%) when body mass is appropriately accounted for. With >85% of the variance in these variables unexplained by this relationship, these findings reaffirm that RE and $\dot{V}O_{2max}$ are primarily determined by independent physiological factors.

Cross-sectional analysis revealed a small positive between-participant relationships between $\dot{V}O_{2max}$ and the metabolic cost of running, when quantified as both E_C (r ~ 0.25) and O_C (r ~ 0.33). These results support the findings of Pate et al. (Pate et al. 1992), who reported a similar relationship (r = 0.29) between submaximal $\dot{V}O_2$ and $\dot{V}O_{2max}$ in a similarly large cohort of habitual distance runners. Conversely, a stronger, moderate positive relationship has been reported between submaximal $\dot{V}O_2$ and $\dot{V}O_{2max}$ in smaller cohorts of elite distance runners (r = 0.59; (Morgan and Daniels 1994)) and physically active individuals (r = 0.48; (Sawyer and Blessinger 2010)). However, all aforementioned investigations are confounded

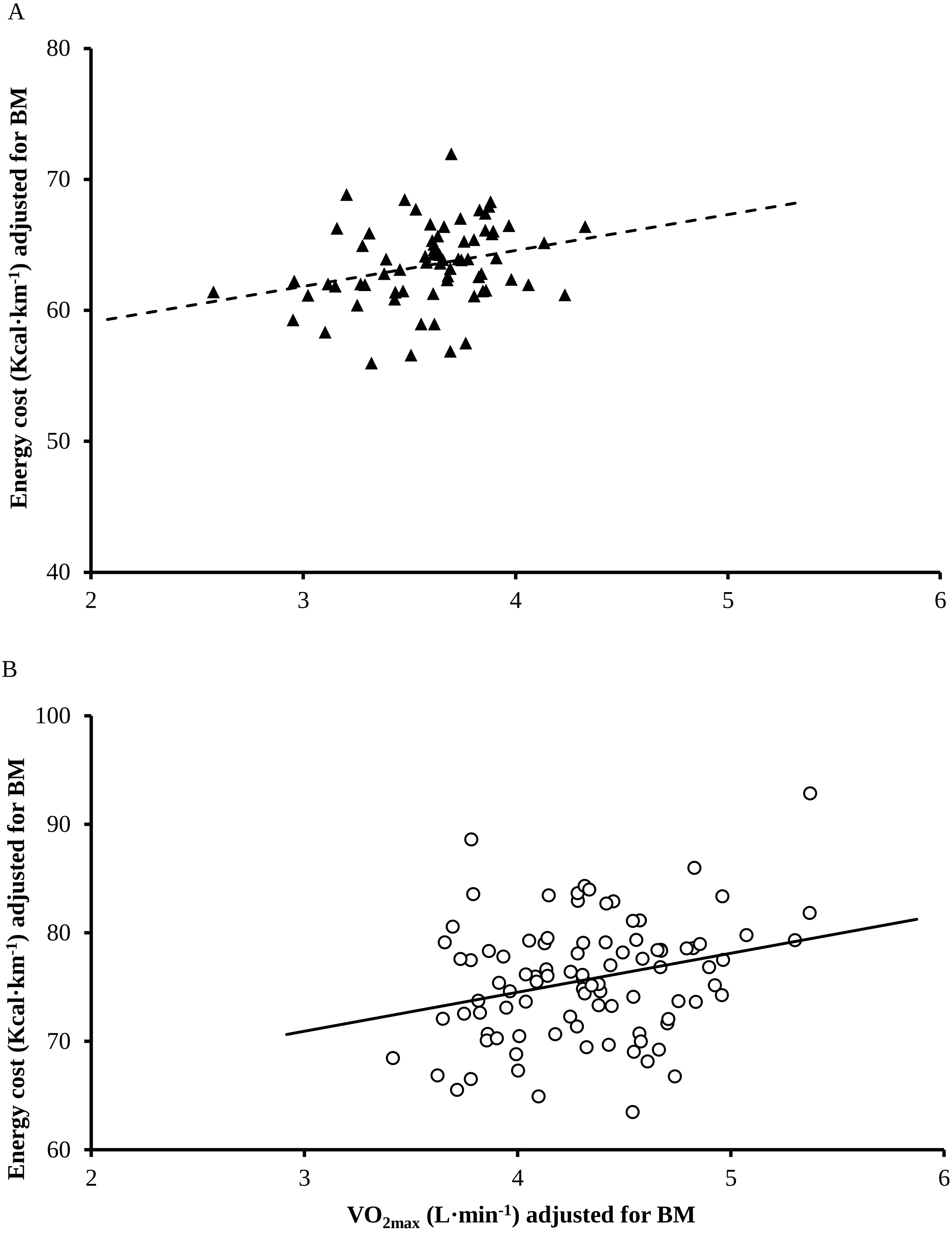

Figure 6.1. Scatter plot of energy cost (Kcal·km^{-1}) adjusted for body mass (BM) vs $\dot{V}O_{2max}$ (L·min^{-1}) adjusted for BM for both females (**A**; n = 70; r = 0.25; P = 0.036) and males (**B**; n = 98; r = 0.26; P = 0.009) in the cross-sectional analysis.

by statistical artefacts that arise when correlating two variables with common divisors (Pearson 1896; Atkinson et al. 2003), and thus should be regarded with caution. Within the current study, spurious correlations between RE and $\dot{V}O_{2max}$ were avoided by removing the influence of body mass with partial correlations, which enabled the true relationship between these variables to be examined. As a lower metabolic cost is reflective of a more economical runner, our findings confirm the existence of a small inverse association between RE and $\dot{V}O_{2max}$ in endurance runners. The longitudinal analysis of the relationship between the changes in RE and the changes in $\dot{V}O_{2max}$ within participants in response to training has not previously been documented. Supporting the findings from our cross sectional analysis, a moderate positive relationship ($r = 0.35$) was observed between the changes in E_C and $\dot{V}O_{2max}$ over repeated assessments. Moreover, these findings support recent observations from competitive road cyclists that highlighted a similar moderate relationship ($r = 0.44$) between changes in gross efficiency and $\dot{V}O_{2max}$ across a training season (Hopker et al. 2012).

It has been postulated that variations in lipid oxidation rates between individuals might, in part, explain the relationship between O_C and $\dot{V}O_{2max}$ that some previous studies have documented; with a higher $\dot{V}O_{2max}$ facilitating greater lipid oxidation and consequently a greater O_C during sub-maximal exercise (Pate et al. 1992). Whilst O_C may be sensitive to lipid oxidation, the calculation of E_C includes the RER and thus is insensitive to differences in substrate metabolism. The influence of substrate metabolism could conceivably explain the marginally stronger relationship observed between O_C and $\dot{V}O_{2max}$, than E_C and $\dot{V}O_{2max,}$ in both the cross sectional ($r \sim 0.33$ vs $r \sim 0.25$) and longitudinal observations ($r = 0.44$ vs $r = 0.35$). More importantly, a positive relationship was documented between E_C and $\dot{V}O_{2max}$ that is clearly independent of variations in lipid metabolism.

The mechanisms that underpin the small relationship between E_C and $\dot{V}O_{2max}$ remain unclear. It has been argued that for athletes of a similar, high performance level, there would be an inevitable relationship between E_C and $\dot{V}O_{2max}$ in order to produce a similar velocity at $\dot{V}O_{2max}$ (Noakes and Tucker 2004). However, we have found no evidence for this possibility, despite all the participants in this study being highly trained and high performing runners, perhaps in part because of the variable performance ability of the athletes.

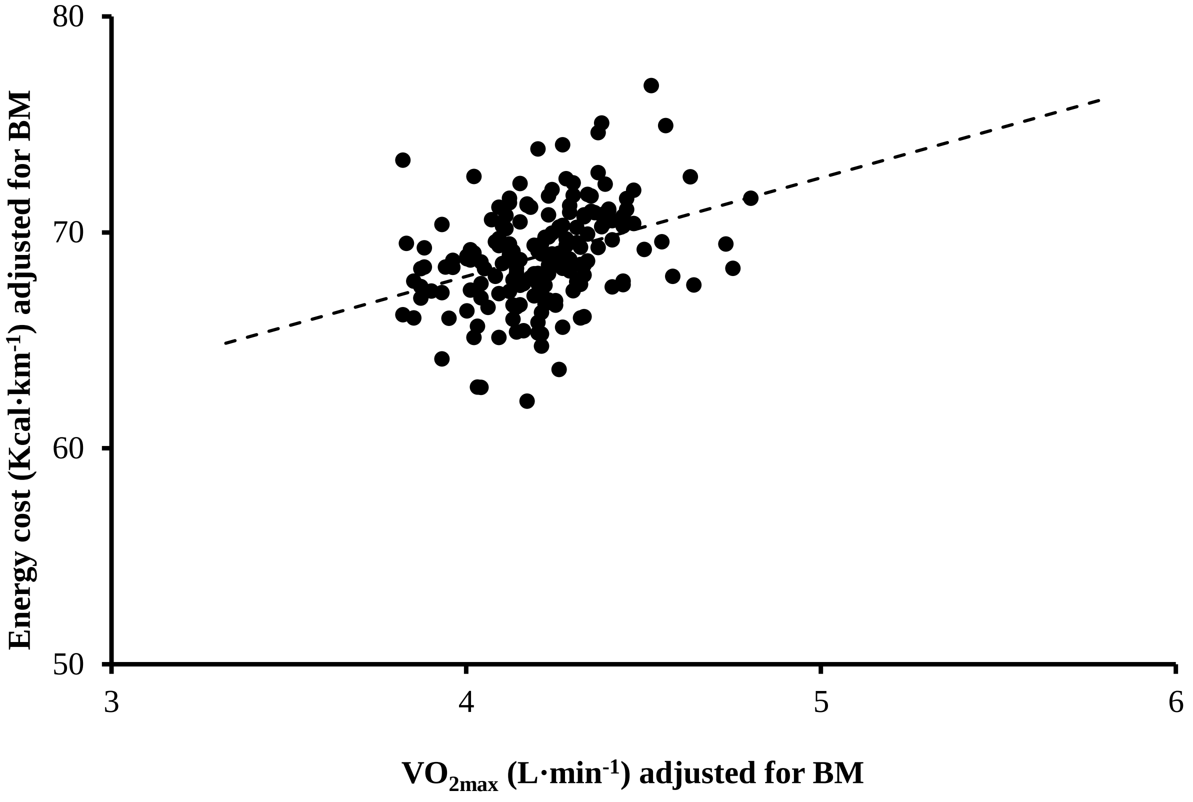

Figure 6.2. Scatter plot of the changes over time in energy cost (Kcal·km-1) adjusted for body mass (BM) vs the changes over time in V̇O2max (L·min-1) adjusted for BM ($r = 0.35$; $P < 0.001$) in the longitudinal analysis.

It is also possible that the recruitment and distribution of muscle mass could provide a potential explanation for these findings. Less economical runners might recruit a larger muscle mass due to excessive braking, oscillation etc. in their running gait, which could conceivably contribute to a higher $\dot{V}O_{2max}$. Moreover, this could be exacerbated by a greater amount of muscle mass carried distally on the lower limbs, increasing the energy requirement during submaximal running (Myers and Steudel 1985; Martin 1985) but also increasing the $\dot{V}O_{2max}$ during maximal running through the activation of a greater volume of mass. However, further investigation would be required to confirm the identity the of factors driving the interdependence of E_C and $\dot{V}O_{2max}$.

Though reaching statistical significance, the association between RE and $\dot{V}O_{2max}$ was small. The current study found only ~ 7% (between-participant cross sectional data) and 12% (within-participant longitudinal data) of the variance in RE was explained by $\dot{V}O_{2max.}$ This small association likely reflects the distinct nature of these variables and their physiological determinants. $\dot{V}O_{2max}$ is known to be determined by factors such as cardiac output (Blomqvist and Saltin 1983), total haemoglobin mass (Schmidt and Prommer 2008), and mitochondrial capacity (di Prampero 2003). Conversely, RE is thought to be closely associated to multiple biomechanical and anthropometrical factors, including effective storage and re-utilisation of elastic energy (Scholz et al. 2008; Hunter et al. 2011), vertical oscillation (Tartaruga et al. 2012) and ground contact time (Di Michele and Merni 2014). As there are few common determinants of both RE and $\dot{V}O_{2max}$, adaptations that lead to enhancements in one of these variables are unlikely to directly influence in the opposing variable.

In conclusion, the current investigation demonstrates that only a small to moderate relationship exists between running economy and $\dot{V}O_{2max}$ in highly trained distance runners. With >85% of the variance in these variables unexplained by this relationship, these findings reaffirm that running economy and $\dot{V}O_{2max}$ are primarily determined by independent physiological factors.

CHAPTER VII

The efficacy of supplementary downhill running as a method to enhance running economy in highly trained distance runners

7.1 Introduction

Running economy (RE), defined as the energy cost to cover a given distance, is a primary physiological determinant of endurance running performance (di Prampero 2003; Ingham et al. 2008). In populations where the differences in athletic capabilities are small, the combination of running economy and maximal oxygen uptake ($\dot{V}O_{2max}$) can account for >90% of the variability in performance (McLaughlin et al 2010). In addition, improvements in $\dot{V}O_{2max}$ for athletes with already high capacities are difficult to achieve (Hopker et al. 2009; Lucia et al. 2000; Jones 2006; Iaia et al. 2009), therefore methods to enhance running economy are sought after to maximise an athlete's performance. However, established training interventions that can improve running economy in already well trained runners are limited.

Previous investigations have explored the use of strength training and plyometric training as methods to enhance running economy in trained distance runners. Through the addition of lower-limb strength and/or plyometric training into endurance running programmes for ~10 weeks, improvements in running economy of 4-8% have been noted (Johnston et al. 1997; Paavolainen et al. 1999; Saunders et al. 2006; Sedano et al. 2013), commonly attributed to neural adaptations that facilitate greater exploitation of the stretch shortening cycle and improved running mechanics (Paavolainen et al 1999; Saunders et al. 2006). Downhill running might facilitate greater time at high velocities of running, due to the lower metabolic cost, and also promote adaptations in stretch shortening cycle function and running mechanics.

Downhill running involves lowering the centre of mass within a stride cycle, releasing gravitational potential energy. When compared to flat or uphill running, downhill running is associated with greater impact loads and higher vertical velocity on landing (Yokozawa et al. 2005; Gottschall and Kram 2005; Neves et al. 2014), resulting in greater eccentric contractions of the extensor muscles of the lower limbs. Consequently, there is greater potential for elastic energy storage and return (Snyder and Farley 2011). Frequent exposure to these higher impact loads and exaggerated stretch-shortening cycle activity could induce a range of adaptations, including higher rates of force development (Cadore et al. 2014) and increased muscle-tendon unit stiffness (Fouré et al. 2010), that promote more effective energy storage and return. In addition, running downhill incurs a lower metabolic cost compared to flat or uphill running (Margaria et al. 1963; Minetti et al. 2002), such that higher velocities can be achieved for the same E_C. Consequently, a greater volume of training at higher speeds may be possible with downhill running compared to running on the flat.

To our knowledge, no previous investigation has examined the physiological responses to extended periods of downhill run training. A one off bout of running down steep gradients (-12-15%) has been shown to cause severe exercise induced muscle damage (EIMD) that has been associated with a transient worsening of running economy (Chen et al. 2007; Chen et al. 2008; Chen et al. 2009; Baumann et al. 2014). However, the use of shallow gradients and a progressive exposure (LaStayo et al. 2000) would be expected to circumvent any EIMD. Therefore, the aim of the current investigation was to assess the efficacy of a supplementary 8 week programme of progressive downhill running as a means of enhancing running economy in well trained distance runners. The downhill running intervention was compared to an equivalent supplementary 8-week programme of intensity matched flat running to isolate the effect of surface gradient. It was hypothesised that prescribed regular downhill running would improve running economy.

7.2 Materials and methods

7.2.1 Participants

Twenty four healthy distance runners were initially recruited to take part in the current investigation, however five athletes withdrew due to either injuries unrelated to the intervention (n = 3), or unforeseen circumstances that resulted in an inability to attend further sessions (n = 2). Subsequently nineteen athletes completed the study (male, *n* = 17; Age: 25 ± 6 years; stature: 179 ± 5 cm; body mass: 68.2 ± 7.2 kg; $\dot{V}O_{2max}$: 73.9 ± 5.5 $mL \cdot kg^{-1} \cdot min^{-1}$; female *n* = 2; Age: 24 ± 5 years, stature: 168 ± 4 cm, body mass: 58.3 ± 6.6 kg, $\dot{V}O_{2max}$: 62.6 ± 1.4 $mL \cdot kg^{-1} \cdot min^{-1}$). Participants' best performance times over the last two seasons were 118 ± 6% of the current British record as of May 2015 in their primary event between 800m and marathon. All participants were treadmill habituated, and provided written informed consent prior to participating in this study that had Loughborough University Ethics committee approval.

7.2.2 **Overview**

Participants were required to visit the laboratory on two occasions per week for 11 consecutive weeks (Figure 7.1). Prior to the initial visits, participants were required to provide an overview of their 'typical' weekly training in the weeks leading up to the investigation, that was categorised based on the 3 zones approach proposed by Seiler et al. (2006). Briefly, marathon pace was defined as zone 1, > marathon pace but < 10 km pace as zone 2, and greater than 10 km pace zone 3 (Table 7.1).

Table 7.1. Participant's weekly run training prior to intervention, categorised by a 3 zone approach (Seiler et al. 2006). Zone 1 < lactate threshold; Zone 2 > lactate threshold, < lactate turnpoint; Zone 3 > lactate turnpoint.

Group	**Total run volume** (miles)	**Zone 1** (% total volume)	**Zone 2** (% total volume)	**Zone 3** (% total volume)
Flat training	54.6 ± 5.2	69 ± 9	16 ± 10	15 ± 3
Downhill training	53.6 ± 7.6	68 ± 9	18 ± 10	14 ± 3

All athletes performed 1 ± 1 gym-based conditioning session per week as part of their habitual training. Participants were then pair matched based on current habitual training, competitive distances and sex, before being randomly allocated to either the flat (n=9) or the downhill (n=10) groups. During the first visit, participants completed a submaximal flat running assessment followed by a maximal running assessment, with ~15 minutes of rest in between. During the same week, participants returned for a second visit to complete a submaximal downhill running assessment. Participants then completed two blocks of 4 weeks of supplementary training where they completed a prescribed treadmill run twice each week (detailed below) on either the flat (1%) or downhill (-5%), interspersed with a week to complete submaximal downhill and flat running assessments to reassess appropriate training speeds. Following the second training block, participants returned to complete post training assessments in an identical format to pre-training. Participants wore appropriate clothing and racing shoes, and laboratory conditions were consistent throughout all running assessments (temperature, 19 ± 1°C; relative humidity, 43 ± 12%), and with similar conditions maintained throughout all training sessions.

7.2.3 **Protocol**

Submaximal running assessments

Following a warm-up (~10 min at 10-12 km·h^{-1}), participants completed a discontinuous submaximal incremental test consisting of six to nine stages of 3 minutes continuous running, with increments of 1 km·h^{-1} on a motorised treadmill of known belt speeds (HP cosmos Saturn, Traunstein, Germany) interspersed by 30 s rest periods for blood sampling. During flat assessments, gradient was maintained at 1% throughout submaximal assessments in order to reflect the energetic cost of outdoor running (Jones and Doust 1996). This protocol has been shown to provide reliable measures of energy cost (typical error ~3%; Chapter 3). During downhill running assessments, the same procedure was followed with the treadmill belt maintained at -5%.

The heart rate (HR) response during the warm-up was used to determine a starting speed and provide ~4 speeds prior to lactate turnpoint (LTP). Increments were continued until blood lactate concentration had risen exponentially, typically defined as an increase in blood lactate of ~2 mmol·L^{-1} from the previous stage to enable identification of the velocity at LTP (vLTP) as detailed below. HR (s610i, Polar, Finland) and pulmonary gas exchange (detailed below) were monitored throughout the pre and post training assessments.

Training velocities were then based on vLTP, as this speed represents the highest speed where valid measures of running economy are still achievable. The vLTP from baseline flat and downhill assessments were used to infer appropriate training velocities for the flat and downhill conditions, respectively, during the first training block, with the vLTP from the mid-assessment used to infer training paces during the second training block.

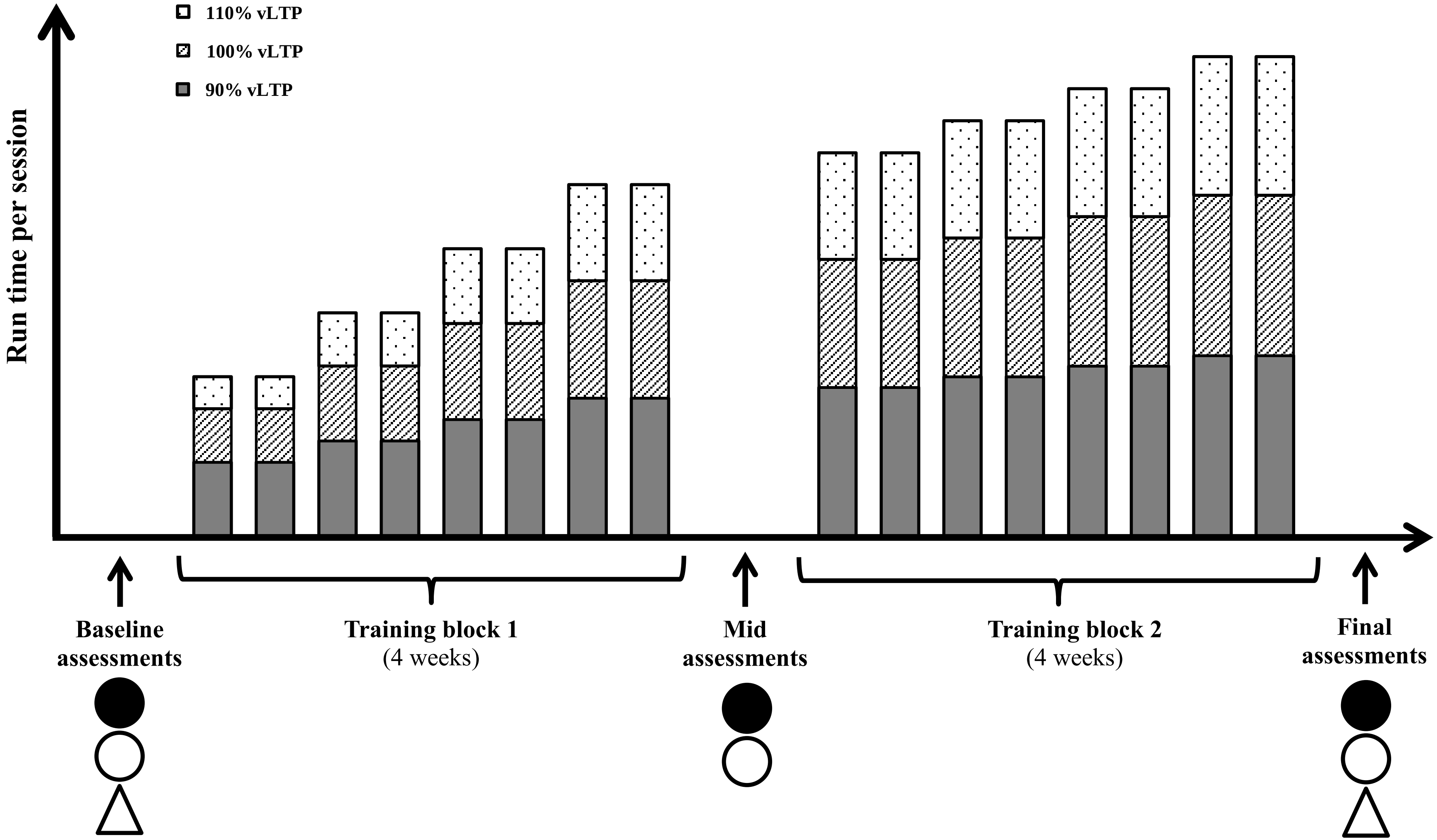

Figure 7.1. Schematic overview of the study. Bars represent running volume per training session, split into the 3 running intensities. Filled circles represent submaximal flat running assessments; Unfilled circles represent submaximal downhill running assessments; Unfilled triangles represent maximal running assessments.

Maximal running assessments

$\dot{V}O_{2max}$ was determined by a continuous incremental treadmill running ramp test to volitional exhaustion. Participants initially ran at a speed 2 km·h^{-1} below the final speed of the submaximal test and at a 1% gradient. Each minute, the incline was increased by 1% until volitional exhaustion. The test duration was typically 6-8 minutes.

Supplementary training interventions

Two progressive 'tempo' training sessions were included in each athlete's weekly habitual training programme during both of the 4 week training blocks (Figure 7.1). To accommodate the supplementary training, athletes typically replaced an existing sessions of a similar intensity in their habitual programme with the prescribed sessions. Participants completed the prescribed sessions in their weekly programme at a time of their own discretion. During the first training session, following a light warm up (~10 mins at ~11-12 km·h^{-1}), participants completed 7 mins of running at 90% of the gradient specific vLTP that led continuously into 5 mins at 100% vLTP. Participants then rested for 3 minutes, followed by a final 3 minutes at 110% vLTP. The same session was then repeated within 7 days, with volume incrementally increasing for each additional week. For the following 3 weeks, 2 minutes were added to each intensity (i.e. by week 4: 13 mins at 90%vLTP, 11mins at 100%vLTP and 9 mins at 110%vLTP). There was a 3 min rest period between the 100%vLTP and 110%vLTP efforts. To ensure athletes could achieve the total duration prescribed at 110%vLTP this period was divided into intervals that were ≤ 3 mins with 90s rest between intervals (i.e. 7 mins spilt into 3 x 2 min 20 second intervals, 9 mins into 3 x 3min intervals). During the second 4-week block the duration at each intensity was only increased by 1 min·week^{-1}. As a result, the final two training sessions involved 17 mins at 90% vLTP, 15 mins at 100% vLTP and 13 mins (5 x 2 min 36 s) at 110% vLTP. All supplementary training sessions were supervised by the principle investigator.

7.2.4 **Measurements**

Anthropometry

Prior to exercise during visits for submaximal running assessments, body mass was measured using digital scales (Seca 700, Seca, Hamburg, Germany) to the nearest 0.1 kg. Stature was recorded to the nearest 1 cm using a stadiometer (Harpenden Stadiometer, Holtain Limited, UK). Using calibrated callipers (Harpenden, Holtain Limited, UK), body composition was assessed at pre- and post-intervention using an 8 site skinfold method (bicep, tricep, subscapular, illiac crest, supra-illiac, abdonmen, thigh and calf), performed by ISAK trained personnel. The total of the 8 sites was then calculated and used as an index of fat mass.

Pulmonary gas exchange

Breath-by-breath gas exchange data were quantified via an automated open circuit metabolic cart (Oxycon Pro, Carefusion, San Diego, USA). Participants breathed through a low dead-space mask, with air sampled at 60 $mL{\cdot}min^{-1}$. Prior to each test, two point calibrations of both gas sensors were completed, using a known gas mixture (16% O_2, 5% CO_2) and ambient air. Ventilatory volume was calibrated using a 3 L (±0.4%) syringe. Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$) and RER values were quantified over the final 60 s of each stage in both submaximal protocols. $\dot{V}O_{2max}$ was defined as the highest average breath-by-breath $\dot{V}O_2$ over a continuous 30s sample during the maximal running assessment, expressed relative to body mass ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$). Solving the regression equation describing $\dot{V}O_2$ and speed for the incremental intensities during the submaximal flat running assessment calculated the velocity associated with $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$). The utilisation of $\dot{V}O_{2max}$ at vLTP (%vLTP) was calculated pre and post intervention by expressing $\dot{V}O_2$ at LTP as a percentage of $v\dot{V}O_{2max}$.

Blood lactate

Between submaximal running stages 20µL of capillary blood was sampled from the earlobe for analysis of blood lactate (Biosen C-line, EKF diagnostics, Germany). LTP was identified by two independent practitioners, based on the Thoden model that defines LTP as the running speed above which blood lactate concentration increased by >1.0 $mmol{\cdot}L^{-1}$ from the previous stage (Thoden 1991).The four stages prior to LTP were identified for each participant during flat (LTP_F) and downhill running (LTP_D), with an average of these four stages used to quantify energy cost.

Calculation of running economy

$\dot{V}O_2$ and $\dot{V}CO_2$ during the final minute of each submaximal stage were used to calculate E_C. Updated nonprotein respiratory quotient equations (Péronnet and Massicotte 1991) were used to estimate substrate utilisation (g·min^{-1}) during the monitored period. The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolised substrates during moderate to high intensity exercise (Jeukendrup and Wallis 2005). Energy cost was quantified as the sum of these values, expressed in kcal·km^{-1}, for both flat running (RE_F) and downhill running (RE_D).

Biomechanical parameters

As all stride parameters are known to be influenced by absolute running speed, the following analysis was conducted at a standardised speed of 16 km·h^{-1} to enable interindividual comparisons. This speed was selected due to being common through all submaximal assessments on both gradients. A photoelectric cell system (Optojump, Microgate, Bolzano, Italy) was used to measure ground contact time, flight time, stride length and stride frequency over the final 60s of each running stage during the submaximal flat and downhill running assessments. The system consisted of two parallel units (a transmitter and a receiver), set on opposing sides of a 2 m section of the treadmill belt. The photoelectric system was positioned 0.3 cm above the plane of the treadmill belt and each transmitter contained 96 equidistant LEDs per meter, recording at 1 kHz. All parameters were quantified using the Optojump Next software (v 1.9.9.0). Data were filtered to remove erroneous values >2 standard deviations away from the mean. Due to equipment limitations, observations were restricted to 12 athletes during flat assessments (downhill training group, n=7; flat training group, n=5) and 11 athletes during downhill assessments (downhill training group, n=7; flat training group, n=4).

7.2.5 Statistical analyses

Data analysis was conducted using SPSS for windows (v21; IBM Corporation, Armonk, NY). Normal distribution of the dependent variables was confirmed via Shaprio-wilk tests, and the variance was found to be homogenous where 3 time points were assessed. Paired sample t-tests were used to assess any differences between groups at baseline for the training, anthropometrical, physiological and stride characteristics assessed. Pearson's product-moment correlation coefficient between measures of E_C (Kcal·kg^{-1}·km^{-1}; averaged over the 4 stages prior to LTP) and body mass from the first submaximal flat running assessment were used to assess the appropriateness of linear modelling to remove the influence of body mass in accordance with chapter 3. The effect of the training interventions on the physiological variables and stride parameters were assessed within groups via paired samples t-tests, with two (Group; Downhill training and Flat training) by two (Time; Pre and Post) mixed measures ANOVA used to assess differences in the responses between interventions. *Post hoc* analysis with Bonferroni adjustment was used to identify where any significant differences occurred. To assess any relationships between the changes over time in absolute $\dot{V}O_{2max}$ and running economy, partial correlation coefficients were calculated using ANCOVA (Bland and Altman 2009), with 95% confidence intervals. Data are presented as mean ± SD for all dependant variables, with significance differences accepted at $P \leq 0.05$.

7.3 **Results**

No differences were observed in age (27 ± 6 and 23 ± 5 yrs) or stature (177 ± 5 and 179 ± 5cm) between the flat and downhill training groups at baseline, nor were any differences noted in other anthropometrical, training, physiological or biomechanical characteristics (Table 7.1; Table 7.2; Table 7.3). Body mass remained consistent across the study period for both flat and downhill groups (t-test, P=0.10 and P=0.93; respectively; group x time interaction effect, P = 0.19). Sum of 8 skinfolds decreased post intervention in the flat training group (P = 0.05) with no change in the downhill group (P = 0.14). However, no time x group interaction effect was present (P = 0.48). Pearson’s correlations confirmed the appropriateness of linear modelling to remove the influence of body mass on E_C (R^2=0.10; P=0.20).

7.3.1 **Flat running assessments**

No differences in RE_F were evident between pre and post assessments in the downhill (P = 0.41) or flat training group (P = 0.68), with no group x time interaction effect (P = 0.89; Figure 7.2a). LTP_F increased from pre to post assessments in the flat (P = 0.05) and downhill training group (P = 0.02), however no group x time interaction effect was present (Table 7.3). An increase in %vLTP was evident when groups were combined (Main effect of time, P =0.05), however no interaction effect was present. Further, no significant increases from pre to post assessments were noted in the percentage utilisation of $v\dot{V}O_{2max}$ at vLTP within the downhill (86.2 ± 8.0% vs 89.4, P=0.19) or flat training group (86.5 ± 4.5% vs 89.1 ± 4.5%, P=0.11), respectively, when analysed separately.

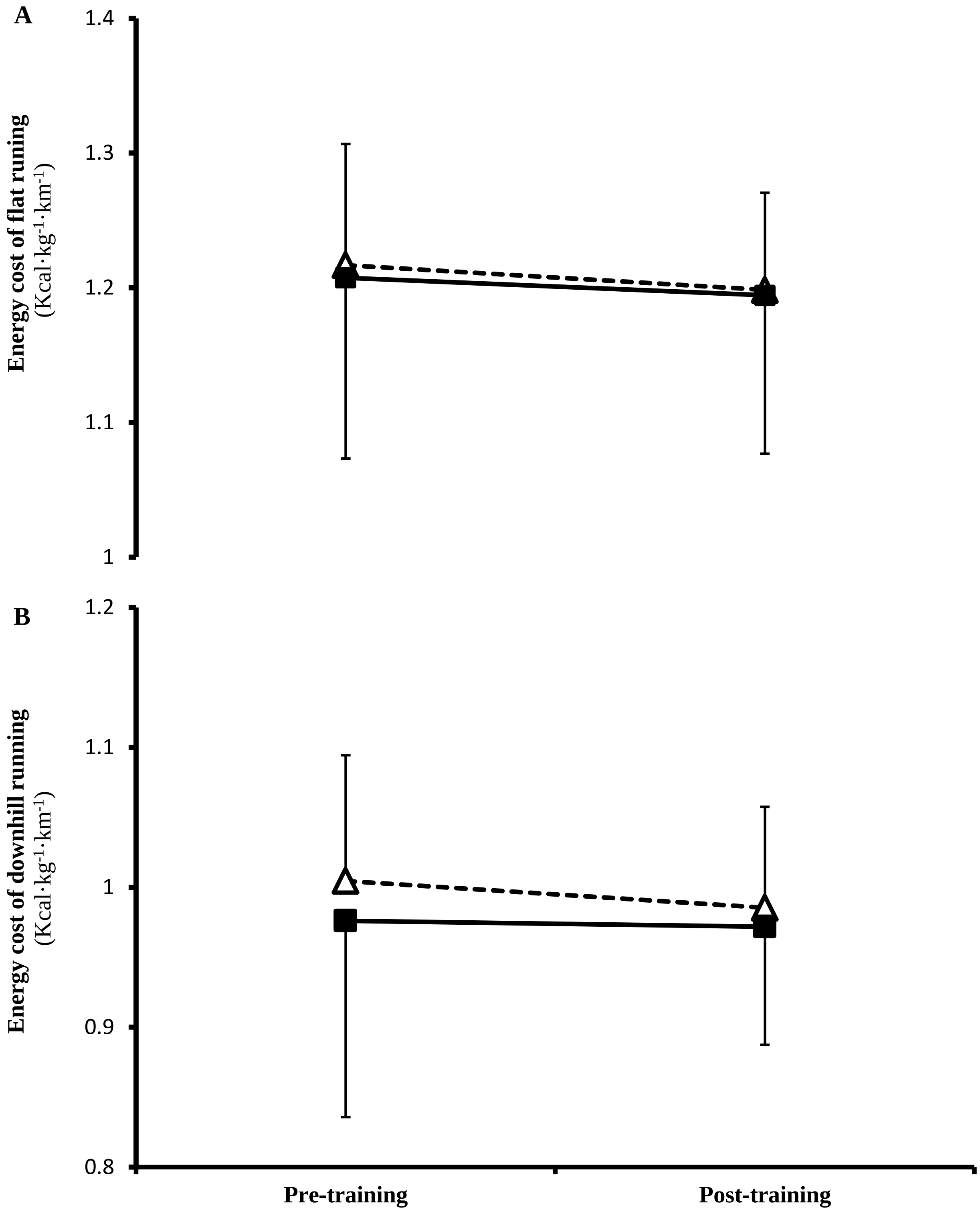

Figure 7.2. Energy cost pre- and post-8 weeks of supplementary training in the flat (Solid squares, solid line) and downhill (Open triangles, dashed line) training groups during submaximal **A**. flat and **B**. downhill running assessments.

Table 7.2. Anthropometric and physiological variables assessed at baseline and post 8 weeks of prescribed training.

	Flat training		**Downhill training**	
	Pre	***Post***	***Pre***	***Post***
Body mass (kg)	68.2 ± 7.9	67.2 ± 8.1	66.2 ± 7.7	66.1 ± 7.4
Skinfolds (mm)	55.0 ± 22.9	50 ± 17.9	48.6 ± 15.4	45.7 ± 10.9
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	72.9 ± 6.7	72.6 ± 5.9	72.6 ± 6.7	70.7 ± 4.9
$v\dot{V}O_{2max}$ ($km \cdot h^{-1}$)	19.7 ± 1.6	19.5 ± 1.3	19.2 ± 1.3	19.1 ± 1.0

$\dot{V}O_{2max}$, maximal oxygen uptake; $v\dot{V}O_{2max}$, flat running velocity associated with maximal oxygen uptake

No differences in $\dot{V}O_{2max}$ or $v\dot{V}O_{2max}$ were noted between pre and post assessments in either condition (Table 2), nor were any group x time interaction effects present ($P = 0.38$ and $P = 0.55$). Partial correlation analysis from ANCOVA revealed no significant relationship between the changes in running economy and $\dot{V}O_{2max}$ over time ($r = 0.34$; CI -0.17 – 0.70; $P = 0.16$).

For biomechanical variables, there were no changes between pre and post assessments ($P>0.33$), or group x time interaction effects, for flight time, stride length and stride frequency during running on the flat (Table 7.3). ANOVA revealed a significant group x time interaction effect for ground contact time, indicating the changes in ground contact over the intervention period were different between groups. Post hoc analysis revealed no differences in contact time between groups post intervention ($P = 0.64$) and within group t-tests revealed contact time displayed a non-significant increase in the flat training group ($P = 0.09$) and a non-significant decrease in the downhill training group ($P = 0.18$) post training.

7.3.2 Downhill running assessments

No differences in RE_D were evident between pre and post assessments in the downhill ($P = 0.23$) or flat training group ($P=0.87$), with no interaction effect present between groups ($P=0.61$; Figure 7.2b). LTP_D increased from pre to post assessments in the downhill ($P = 0.02$) and flat training group ($P = 0.04$), however no interaction effect was present (Table 7.3). The %vLTP remained consistent for both the downhill (82.5 ± 7.9% vs 85.3 ± 6.9%, $P=0.21$) and flat training groups (82.7 ± 5.2% vs 84.4 ± 3.6%, $P=0.43$) from pre to post assessments, respectively. Flight time, stride frequency, stride length and ground contact time remained unchanged during downhill running assessments following training in both groups ($P>0.11$), with no group x time interactions (Table 7.3).

7.4 **Discussion**

The aim of the current investigation was to evaluate the efficacy of a supplementary downhill run training programme as a means to enhance the running economy of well-trained distance runners. We found that 8 weeks of additional downhill or flat run training at vLTP in existing training programmes did not change running economy. Both training groups showed improvements in vLTP of both flat and downhill running, and therefore these improvements were not specific to the training gradient. However, no changes in $\dot{V}O_{2max}$ or velocity of $\dot{V}O_{2max}$ were evident in either condition. Contrary to our hypothesis, a short programme of supplementary downhill run training did not enhance running economy in already well trained individuals.

The influence of chronic downhill training on running economy has not previously been documented. It was proposed that downhill running could facilitate greater training time at high running velocities, in addition to exposure to high impact forces, which could lead to adaptations in stretch shortening cycle function and running mechanics; and thus improvements in running economy. Due to the reduced E_C for a given exercise intensity, training velocities were ~2 $km \cdot h^{-1}$ greater in the downhill group compared to the flat training group. However, despite the exposure to higher running velocities and greater impact forces in the downhill training group, no changes in running economy were observed after 16 sessions of downhill run training in already well trained individuals.

In contrast, traditional plyometric training has been shown to increase running economy in trained endurance athletes over a similar time frame (Paavolainen et al. 1999; Saunders et al. 2006), attributed to concurrent changes in surrogate measures of neuromuscular adaptations (i.e. ground contact times, 5 jump plyometric test performances) that could lead to a greater exploitation of the stretch-shortening cycle. However, no changes in running mechanics were observed following downhill run training in the current investigation.

Table 7.3. Physiological and biomechanical variables assessed pre and post 8 weeks of prescribed training in the flat and downhill training groups.

	Flat training		**Downhill training**		**ANOVA (group x time; P=)**
	Pre	***Post***	***Pre***	***Post***	
Flat Running					
LTP_F ($km \cdot h^{-1}$)	16.9 ± 0.7	17.2 ± 1.0*	16.5 ± 0.7	16.9 ± 0.6*	0.53
Ground contact (s)	0.20 ± 0.02	0.21 ± 0.01	0.21 ± 0.01	0.20 ± 0.01	0.03
Stride length (m)	3.02 ± 0.21	3.07 ± 0.12	2.96 ± 0.12	3.01 ± 0.19	0.98
Stride frequency ($Strides \cdot min^{-1}$)	176 ± 14	174 ± 7	178 ± 7	179 ± 6	0.64
Flight time (s)	0.14 ± 0.02	0.14 ± 0.02	0.13 ± 0.02	0.13 ± 0.02	0.64
Downhill Running					
LTP_D ($km \cdot h^{-1}$)	19.3 ± 1.0	19.7 ± 1.3*	18.5 ± 0.8	19.1 ± 0.8*	0.53
Ground contact (s)	0.20 ± 0.02	0.21 ± 0.01	0.20 ± 0.02	0.20 ± 0.01	0.21
Stride length (m)	3.10 ± 0.20	3.18 ± 0.15	3.00 ± 0.05	3.05 ± 0.05	0.44
Stride frequency ($Strides \cdot min^{-1}$)	170 ± 12	169 ± 8	176 ± 4	177 ± 5	0.27
Flight time (s)	0.15 ± 0.02	0.15 ± 0.01	0.14 ± 0.02	0.14 ± 0.02	0.74

* - denotes significant difference to pre-assessment ($P \leq 0.05$). RE_D, downhill running economy; LTP_F, lactate threshold for flat running; LTP_D, lactate threshold for downhill running

It is possible that the highly trained status of the current cohort could, in part, explain the lack of change in running economy in the current investigation. Despite no previous exposure to structured downhill running, participants all performed high intensity training and resistance based conditioning sessions in their habitual training; matching previous observations from high performance endurance runners (Esteve-Lanao et al. 2005; Enoksen et al. 2011; Ingham et al. 2012). In contrast, previous investigations have commonly observed athletes that had minimal resistance training experience (Saunders et al. 2006; Guglielmo et al. 2009; Taipale et al. 2010; Taipale et al. 2013), or following extended periods (> 6 weeks) of no resistance training (Johnston et al. 1997; Barnes et al. 2013). Consequently, the changes in running economy in these previous studies could reflect the rapid neural adaptations and learning effect that occur in response to initial bouts of resistance training in unaccustomed athletes, rather than the morphological and neural adaptions that occur with continued exposure (Folland and Williams 2007). Indeed, when additional strength and/or plyometric training has been incorporated into the training programmes of resistance trained endurance athletes, no change (Millet et al. 2002) or small improvements (~3%) in running economy have been reported after comparably long exposures of 12-14 weeks. Though changes did not reach significance in the current study, running economy improved by 1.5% at a group level following downhill training, which is comparable to the smallest worthwhile change in this variable (Chapter 3); the threshold for when a change is viewed as meaningful. It is therefore plausible that the short term intervention with a comparatively modest stimulus from downhill running could have been insufficient to promote the neuromuscular adaptations commonly associated with plyometric training in this population, despite its modality specificity.

It has been proposed that athletes are most economical at velocities at which they habitually train (Jones and Carter 2000). Consequently, it could be argued that training at a prescribed velocity itself could provide an efficacious method to enhance running economy at that given velocity. However, in line with the downhill training group, no change was observed in running economy around vLTP for athletes performing intensity matched flat running. These findings support previous investigations where no improvement in running economy at vLTP was noted following prescribed training at vLTP in recreational (Yoshida et al. 1990) and highly trained runners (Sjodin et al. 1982). Whilst it is possible that a longer exposure could be required due to the highly trained status of the cohort, no changes in running economy at speeds close to vLTP have been observed across a competitive season in highly trained runners, despite a notable training volume around this velocity (Galbraith et al. 2014). Our findings therefore suggest that structured flat running around vLTP does not improve running economy in already well trained athletes.

Similar to RE, no changes in $\dot{V}O_{2max}$ were apparent following 8 weeks of training in either condition. These findings are in accordance with previous observations from trained runners, where $\dot{V}O_{2max}$ has remained consistent following the introduction of additional training at vLTP (Sjodin et al. 1982; Yoshida et al. 1990), and interval training at and above vLTP (Billat et al. 2002; Denadei et al. 2006; Barnes et al. 2013) into habitual training programmes. As training at or around $v\dot{V}O_{2max}$ has been postulated to be the most effective way to enhance $\dot{V}O_{2max}$ in well trained athletes (Midgey et al. 2007), it is possible that the submaximal intensities employed created an insufficient stimulus to prompt significant alterations in the maximal capacities of the groups.

In contrast, increases in both LTP_F and LTP_D were noted following the downhill (2.4 and 3.2%, respectively) and flat training (1.8 and 2.0%, respectively). These findings support previous reports where enhancements in LTP_F have been observed following the incorporation of additional run training around vLTP in trained runners (Sjödin et al. 1982; Billat et al. 2004). Our findings add greater detail to these findings, as they demonstrate that the improvements in vLTP are not gradient dependant. Given the absence of significant improvements in the primary physiological determinants assessed the improvements in LTP_F and LTP_D could instead reflect a composite of the subtle, yet non-significant, enhancements in %vLTP (~3% in both conditions) and RE noted. Moreover, due to the consistency of stride parameters on both gradients, the improvement in vLTP could be mediated by an enhancement in the metabolic profile of the recruited muscles, such as mitochondrial biogenesis and elevated oxidative enzyme concentrations/activity (Holloszy and Coyle 1984; Bassett and Howley 2000), thus translation of improvements in vLTP to other shallow gradients would be expected.

In conclusion, our data indicate that 8 weeks of supplementary downhill run training at vLTP within existing training programmes does not enhance running economy of already well trained runners. Given the importance of running economy to endurance performance, further investigations are required to elucidate practical and accessible methods to enhance running economy in already well trained athletes.

CHAPTER VIII

General discussion

8.1 Summary

Running economy (RE) has long been established as a primary determinant of endurance running performance (Daniels 1985; Bassett and Howley 2000; Jones and Carter 2000; di Prampero 2003; Jones 2006; Joyner and Coyle 2008; Ingham et al. 2008), with evidence to suggest that RE can account for large proportions of the variance in performance of elite middle distance (Ingham et al. 2008) and long distance runners (Conley and Krahenbuhl 1980). Despite appearing fundamental to elite endurance running performance, robust methods to enhance the RE of already high performing, highly trained runners are limited; potentially restricted by the absence of 1) a common consensus of how to define and quantify RE, and 2) methods to identify the primary limiting factors of an athlete's RE. Therefore, this thesis investigated the RE of highly trained runners, exploring the reliability and validity of measures of RE to deduce its most appropriate quantification, in addition to the application of innovative methods to enhance our understanding of an athlete's RE. Finally, this thesis explored a novel training method to enhance RE in this population. The main findings of the thesis were as follows:

1. Energy cost (E_C) and oxygen cost (O_C) provided similarly high levels of reliability (typical error of measurement ~3%) for highly trained endurance runners when assessed using a short-duration incremental submaximal exercise protocol. The typical error of measurement was greater than the smallest worthwhile change (~1.5%) for both expressions, indicating that only when test-retest alterations in E_C or O_C exceed 3% can practitioners confidently interpret a meaningful change in RE (Chapter 3).
2. The analysis of a large cohort of highly trained endurance runners revealed that E_C increased in a stepwise manner with increments in running speed ($P<0.001$). However, no differences were observed for O_C despite an incremental increase in running speed ($P=0.54$). The results suggested that E_C could provide a more appropriate quantification of RE in highly trained runners. (Chapter 4).

3. The inter-individual variation in the E_C responses from flat running to uphill or downhill running was low in a cohort of highly trained runners, with strong associations between E_C during flat running and E_C when running on shallow positive (+5%; r=0.85) and negative (-5%; r=0.90) gradients. However, a disparity between the energy saving of running downhill (-17% vs E_C flat) and the additional energy cost of running uphill (+32% vs E_C flat) was evident (Chapter 5).
4. The cross-sectional analysis of a large cohort of highly trained runners, with appropriate partial correlation analysis, revealed a small (r=0.25) association between E_C and $\dot{V}O_{2max.}$ Further, a longitudinal analysis of a sub-cohort revealed a moderate (r=0.35) association between changes in E_C and $\dot{V}O_{2max}$ over time. As >85% of the variance in E_C and $\dot{V}O_{2max}$ remained unexplained by this relationship, these findings reaffirm that E_C and $\dot{V}O_{2max}$ are primarily determined independently (Chapter 6).
5. Eight weeks of downhill run training at vLTP included in existing training programmes did not enhance running economy of already well trained runners (1.22 vs 1.20 $kcal \cdot kg^{-1} \cdot km^{-1}$; P=0.41; Chapter 7).

8.2 The empirical and practical implications of the findings

8.2.1 Measuring running economy in trained distance runners

Chapters 3 and 4 aimed to establish the most valid and reliable expression of RE in highly trained runners. From its inception, the metric of RE has uniformly been used to describe the translation of aerobic metabolism into linear running velocity. However, the definition and quantification of RE is not uniform across all empirical investigations. The differing protocols and quantifications employed to assess RE would appear to limit the interpretation of findings, not only restricting direct comparisons between empirical investigations, but also clouding the identification of accurate normative values for RE. The inconsistency in this measurement is likely to have contributed heavily to the limited progress of the scientific community to truly understand the RE of an athlete, despite a relatively high volume of empirical investigations in the last decade. Indeed, the concluding remarks of a recent review by Lacour & Bourdin (2015) drew attention to this, stating that “more attention should be paid to measurement validity”.

The validity of the different quantifications of RE has received a growing amount of attention following an investigation by Fletcher and colleagues (2009), where a disparity was shown in the responses of E_C and O_C to increments in running speed in a small cohort of runners. In agreement with these preliminary findings, our findings from a very large cohort of highly trained endurance runners demonstrated that although E_C increased with increments in running speed, O_C remained unchanged as speed increased (Chapter 4). The discrepancy in these responses is likely to be a product of the sensitivity of O_C to the concurrent alteration in substrate utilisation seen in the investigation. Given E_C and O_C do not respond in a consistent manner, the question of 'which quantification provides the most appropriate and valid expression?' arises.

In accordance with the recent reviews of the literature (Saunders et al. 2004d; Barnes et al. 2015; Lacour and Bourdin 2015), RE reflects the aerobic energy demand of running at a constant submaximal speed. Therefore, the quantification of RE as O_C would appear to be based on the assumption that steady state $\dot{V}O_2$ provides an index on the underlying ATP turnover during submaximal exercise (Fletcher et al. 2009), or at least proportional to it (Saunders et al. 2004b). As E_C provides the actual indirect assessment of energy turnover, our findings in Chapter 4 suggest that O_C does not represent a valid index of the underlying energy demand of running. However, these findings do not discount the importance of O_C, as it must be noted that previous investigations have shown strong associations between the actual aerobic demand and performance, rather than energy expenditure per se (Conley and Krahenbuhl 1980; Ingham et al. 2008). Moreover, as O_C is a product of both E_C and substrate utilisation, both of which could have an independent influence on endurance performance, it is likely that O_C represents a stronger predictor of endurance performance than E_C alone. However, the distinction between O_C and RE can be summarised in Figure 8.1. As both E_C and substrate utilisation would appear to be two independent variables that could be manipulated by training interventions, considering E_C and substrate utilisation separately could enhance the interpretation of findings in this field. The benefit of independent measures was clearly demonstrated in Chapter 6, where a further insight into RE was achieved with the findings of a weaker relationship between RE and $\dot{V}O_{2max}$ when expressed as E_C rather than O_C, indicating a small inverse association between $\dot{V}O_{2max}$ and RE that was independent of substrate utilisation. It is therefore proposed that E_C should form the primary quantification of

RE in future research, with findings of Chapter 4 demonstrating an appropriate expression of $Kcal \cdot kg^{-1} \cdot km^{-1}$ to facilitate inter-individual comparisons.

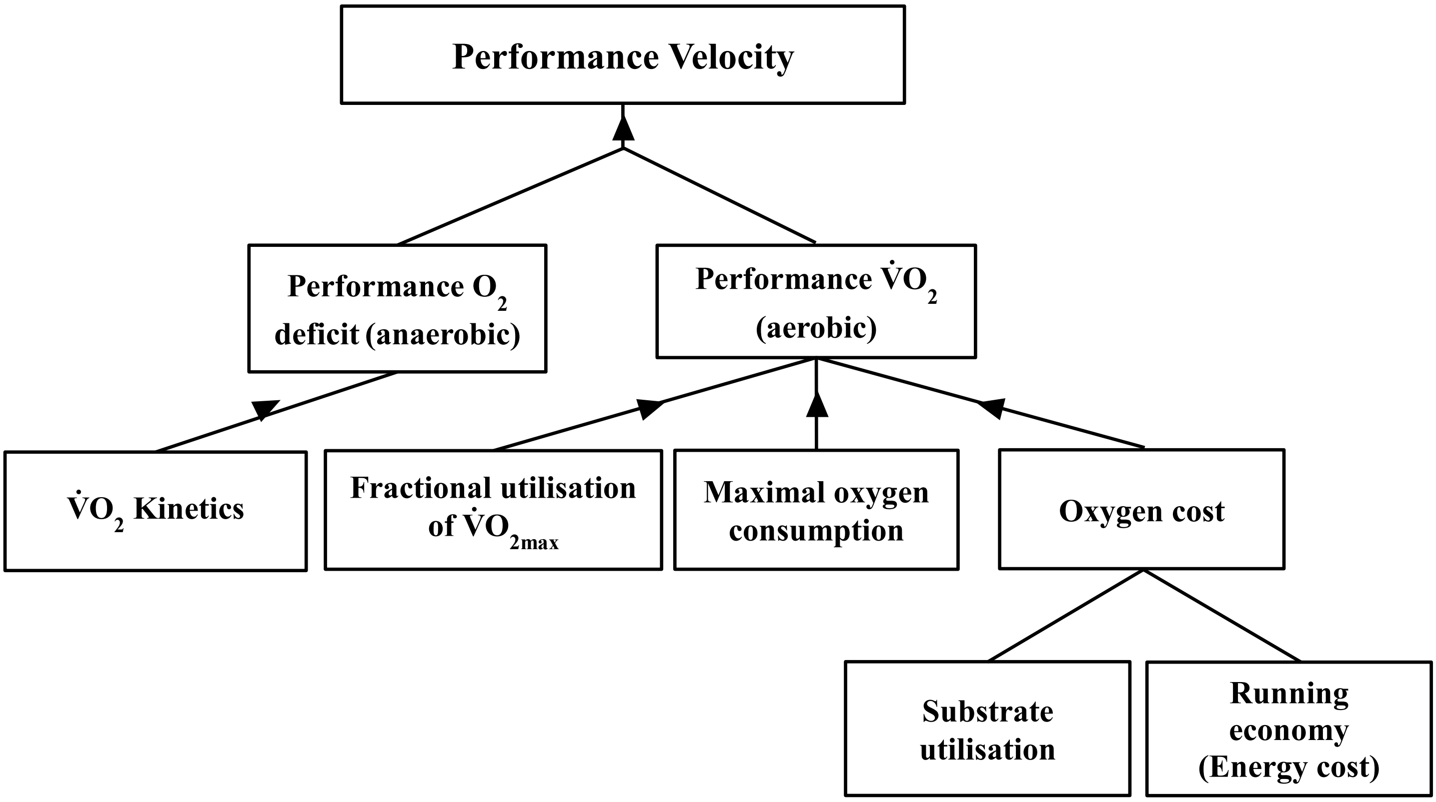

Figure 8.1 A revised schematic representation of the physiological factors that interact to determine performance velocity in endurance running events.

A second factor that must be considered in the measurement of RE is the reliability of measures, describing how stable and repeatable the assessments are. The assessment of reliability is critical to the interpretation of findings, providing a quantitative assessment of the confidence that a true change in RE has occurred following an intervention, that is, the ability to differentiate a signal from the inherent noise of the measurement. Previous investigations have explored the reliability of O_C measures over 2-35 visits, with a typical error of measurement (TE) of ~2-3% (Williams et al. 1991; Pereira et al. 1994; Brisswalter and Legros 1994b; Pereira and Freedson 1997; Saunders et al. 2004a). Chapter 3 substantiates these findings, and furthers the field by demonstrating a comparable level of reliability for E_C (TE ~3%). These findings indicate that only when changes in RE exceed ~3% can a change be confidently interpreted as a true change when employing similar protocols.

The findings of Chapter 3 also revealed that the TE for both O_C and E_C were almost double the smallest worthwhile change (SWC) in these variables (~1.5%). As the SWC represents the threshold for when a change becomes meaningful (Hopkins 2004), it could be argued that further work is required to enhance the reliability of RE measures to be able to confidently detect the SWC. In attempts to maximise reliability, previous investigations have employed elongated stage lengths to ensure the achievement of steady-state gaseous exchange (Morgan et al. 1991; Williams et al. 1991; Pereira and Freedson 1997), in addition to experimental-style controls to minimise the variations in substrate utilisation during the exercise bout (Williams et al. 1991; Pereira et al. 1994; Pereira and Freedson 1997). However, Chapter 3 demonstrated an achievement of steady state conditions during the final minute of each 3 minute running stage in >90% of cases, likely reflecting the fast phase II kinetic responses observed in endurance trained athletes (Koppo et al. 2004). Moreover, in addition to E_C providing a measure of RE that was independent of substrate utilisation, the variations in substrate utilisation between assessments were low (TE ~4%), despite no controls for prior nutrition or training. It could further be argued that the use of baseline subtractions of resting values, as employed in Chapter 5, could potentially enhance the reliability of RE. However, as baselines do not remain constant as exercise intensity increases (Stainbsy et al. 1980), and account for a comparatively small proportion of the energy turnover during moderate to severe exercise, this method is unlikely to notably enhance the reliability of RE beyond the current method. It is therefore possible that the achievement of a sufficient level of sensitivity to detect the SWC in RE is unobtainable when employing indirect calorimetry with a highly variable system such as the human body. It is therefore proposed that short-duration (~3 min stages) incremental submaximal running protocols are appropriate for the assessment of RE in highly trained distance runners in both research and practical settings.

8.2.2 **Understanding the running economy of trained distance runners**

It is clear that RE is a complex, multifactorial construct (Saunders et al. 2004d; Barnes and Kilding 2015a; Lacour and Bourdin 2015) with the differences observed between individuals attributed to the weighted sum of the influences from many anthropometrical, biomechanical and physiological variables (Williams and Cavanagh 1987a; Pate et al. 1992). However, investigations exploring methods to identify the specific factors limiting RE in a specific athlete are absent, thus prescription of an effective intervention to improve RE for a given athlete is challenging. Diagnostic tests to identify the strengths and weaknesses underpinning an athlete's RE could be a pivotal step towards the prescription of robust and effective training methods.

It is well established that surface gradient influences RE, with running uphill incurring a greater E_C and downhill a lesser E_C when compared to running on the flat (Margaria et al. 1963; Minetti et al. 2002). When compared to the E_C of flat running, E_C during running uphill would appear to shift towards a greater dependency on metabolic factors, with E_C during downhill running potentially inducing a shift towards a greater dependency on mechanical factors. Thus, high inter-athlete variability in the responses uphill and downhill running could be expected, and could plausibly differentiate the propensity for metabolic and mechanical limitations or constraints, respectively. However, despite notable differences in E_C between gradients, the variability in E_C responses to uphill and downhill running between individuals was limited, with strong associations between flat running and both uphill and downhill running (Chapter 5). These findings demonstrate that a large degree of commonality is evident between E_C on different shallow gradients, with the small changes in gradient employed potentially insufficient to induce a large change in the emphasis between metabolic or mechanical determinants, and thus variation in E_C responses, to identify the specific efficiencies of an athlete.

Despite a wealth of research exploring E_C on positive and negative gradients (Margaria et al. 1963; Minetti et al. 2002; Gottschall and Kram 2005), the difference between the additional cost of uphill running and the reduced cost of downhill running, when compared to flat running, had yet to be considered. Chapter 6 found a disparity was evident between the change in E_C from flat running to shallow uphill and downhill running, with an additional E_C when running on a +5% gradient (+32%) that far outweighed the reduction in E_C when running on a -5% gradient (-17%). The precise mechanisms underpinning this response are unclear. Intuitively, as the increase and decrease in gradient is equivalent between the conditions, a proportional change in E_C could be expected. However, it is possible that the greater vertical oscillation during downhill running could result in an additional E_C (Williams and Cavanagh 1987a; Halvorsen et al. 2012), resulting in a higher E_C on this gradient above that expected. Similarly, the higher work rates of uphill running could lead to recruitment of comparatively inefficient type II muscle fibres (Hunter et al. 2001), resulting in larger than expected energy cost. Though further exploration of the precise mechanisms is required, our findings clearly demonstrate that, for a given gradient, the additional cost of uphill running outweighs the savings during downhill running.

The exploration of the factors affecting RE might have broader implications for endurance runners when applying training methods to enhance RE. Numerous empirical investigations have cited a positive relationship between RE and $\dot{V}O_{2max}$ (Pate et al. 1992; Morgan and Daniels 1994; Fletcher et al. 2009; Sawyer and Blessinger 2010; Barnes et al. 2013), suggesting that those with a superior RE have a tendency for an inferior $\dot{V}O_{2max}$. This association might infer that common determinants exist for both RE and $\dot{V}O_{2max}$, but with opposing influences. Given both RE and $\dot{V}O_{2max}$ are primary determinants of endurance running performance (Conley and Krahenbuhl 1980; Bassett and Howley 2000; Jones and Carter 2000; di Prampero 2003; Joyner and Coyle 2008), targeted training to enhance RE or $\dot{V}O_{2max}$ that alters such common factors might therefore have a negative impact on the opposing variable, thus restricting improvements in performance. However, the previous investigations that explored the relationship between RE and $\dot{V}O_{2max}$ had been limited by small sample sizes and/or inappropriate statistical techniques, thus compromising the interpretation of results. The cross-sectional analysis of a large cohort of trained runners revealed only a small positive association between RE and $\dot{V}O_{2max}$ (Chapter 6). Moreover, the longitudinal analysis demonstrated a moderate positive relationship between changes in RE and changes in $\dot{V}O_{2max}$ over time ($r=0.35$), with the magnitude of this relationship reaffirmed by further analysis of data in Chapter 7 ($r=0.34$). Collectively, the findings of this thesis support previous observations of a small to moderate association between RE and $\dot{V}O_{2max}$.

However, the practical significance of the relationship between RE and $\dot{V}O_{2max}$ has previously been ignored in empirical investigations. Though a statistically significant association is evident between RE and $\dot{V}O_{2max}$, the small to moderate correlation coefficient demonstrates that this association is limited. Further analysis of the explained variance in Chapter 6 demonstrated that >85% of the variation in RE was not explained by the variation in $\dot{V}O_{2max}$. Consequently, although RE and $\dot{V}O_{2max}$ might share common determinants that have opposing influences, the large unexplained variance would suggest that RE and $\dot{V}O_{2max}$ have distinct principle determinants, which is consistent with the current understanding of these variables (Bassett and Howley 2000; Saunders et al. 2004b; Spurway et al. 2012;

Barnes and Kilding 2015a; Lacour and Bourdin 2015). Nevertheless, the identity of the factors that underpin the positive association between RE and $\dot{V}O_{2max}$ remains unclear, but could be related to the recruitment and distribution of muscle mass. It is possible that training methods to enhance the independent determinants of RE could lead to a greater performance improvement by circumventing a reduction in $\dot{V}O_{2max}$. Therefore, future research should be directed towards the identification of the physiological factors that underpin the association between RE and $\dot{V}O_{2max}$ shown in this thesis.

8.2.3 Enhancing running economy in trained distance runners

It is evident that the margin of success for elite endurance runners is extremely small. For example, an analysis of the marathon performances at major competitions over the last 30 years shows an average time gap of 0.4% between the 1st and 2nd placed athletes (www.sports-reference.com). Given the fundamental contribution of RE to endurance running performance (Conley and Krahenbuhl 1980; Ingham et al. 2008), developing and enhancing an athlete's RE would appear to be one of the primary objectives of an athlete's training programme to maximise their probability of success. However, robust training interventions that consistently demonstrate enhancements in RE in already well trained runners are limited (Saunders et al. 2004d; Barnes and Kilding 2015a; Lacour and Bourdin 2015).

Evaluation of the current literature would suggest that the most consistent method to enhance RE in already trained athletes is the inclusion of 6-14 weeks of explosive strength/plyometric training (Paavolainen et al. 1999; Spurrs et al. 2003; Saunders et al. 2006). However, the reports of equivocal findings (Barnes et al 2014) suggest such interventions are far from robust. Moreover, the inclusion of these training practices is often through the partial replacement of endurance training sessions, which could be counterproductive in the athletic development of truly elite endurance athletes. Training methods that could promote similar adaptations to that of explosive strength/plyometric training studies through modality specific endurance training would appear to address these limitations. As downhill running could increase the time spent at higher training velocities, this form of endurance run training could be used to accentuate stretch-shortening cycle activity and facilitate a greater exposure to modality-specific high impact forces, resulting in a range of positive physiological adaptations to enhance RE. However, no significant improvements in RE, or alterations in running mechanics, were observed following 8 weeks of supplementary run training in well-trained distance runners (Chapter 7). Though improvements in vLTP were noted on flat and downhill gradients following downhill training, these improvements were comparable to the intensity matched flat training group; potentially mediated, in part, by subtle enhancements in the percentage utilisation of $\dot{V}O_{2max}$ at vLTP.

Chapter 7 likely highlights the complexities of applying interventions to enhance the RE of already well trained individuals. Though previous investigations have noted improvements in RE following structured run (Billat et al. 1999; Barnes et al. 2013) or strength training (Johnston et al. 1997; Saunders et al. 2006; Guglielmo et al. 2009; Taipale et al. 2010; Taipale et al. 2013) in trained athletes, the populations employed were unaccustomed to the training stimulus of the intervention. However, due to extensive habitual training programmes (Esteve-Lanao et al. 2005; Enoksen et al. 2011; Ingham et al. 2012) and thus a rapid accumulation of a substantial training history, high performance runners are likely to exhibit diminished physiological responses to further training interventions. Indeed, in one of the few empirical observations of an elite distance runners spanning >1 year, only subtle improvements in RE were seen from year to year (Jones 2006). But, the case study revealed an ~15% improvement in RE that accumulated over the full 11 year observation (Jones 2006). Leading experts have speculated that RE might only increase at a rate of 1-3% per year with continued training in elite endurance athletes (Joyner and Coyle 2008). However, there is still little consensus regarding what training drives these changes in RE in an elite athletes training programme, and what physiological changes occur in an athlete that mediates this improvement in RE. Though novel training methods to enhance RE are desirable, future investigations should look to comprehensively monitor the physiological changes that are associated with alterations in RE following explosive strength/plyometric training, such as accurate changes in tendon properties and muscle recruitment patterns, which could in turn provide a greater insight into the primary physiological determinants of this variable.

8.3 Limitations

The limitations of the current thesis are acknowledged. The research presented highlights the dichotomy of investigations with highly trained/elite athletes. Attempts were made throughout the thesis to recruit only high performance athletes, to ensure the findings were as applicable as possible to elite endurance runners. However, as expected, the population of high performance athletes in the local region was small. In addition, many athletes are unwilling to deviate from their ‘typical’ training practices on the premise that performance improvements might be compromised. As the participation in the experimental studies required athletes to manipulate their training schedule to accommodate visits, this limited the population pool further. Therefore, sample sizes in the experimental studies were restricted, and consequently could limit the ecological validity of the investigations.

It should also be noted that although training sessions were tightly regulated in Chapter 7, the prescribed training intervention was supplementary to their habitual training. As the observed cohort was not homogenous with regards to primary race distances, a large inter-athlete variation in training practices could be expected. Consequently, though athletes were pair matched between the training groups, large variability in weekly training was evident in groups, potentially clouding the effect of the prescribed intervention. However, a tighter regulation and prescription of training would not have been feasible with the calibre of competitive athletes recruited.

Both Chapters 4 and 6 were based on the retrospective analysis of physiological data that was collected over a 6-year period. It should be noted that assessments were conducted across 2 laboratories by several different trained practitioners, which could have had a small impact on the consistency of measures. Moreover, though extremely large samples were achieved, the data were not collected for the sole purpose of these investigations. The use of absolute increments in running speed could have resulted in inter-athlete variability in the relative exercise intensity for RE assessments. For example, using the 4 stages below LTP, athlete A with a vLTP of 15 $km \cdot hr^{-1}$ would be assessed across exercise intensities of 73-93% vLTP, whereas athlete B with a vLTP of 19 $km \cdot h^{-1}$ would be assessed across exercise intensities of 79-95%. However, the within sex variability in vLTP was small (<7% for 95% of the population across all monitored stages), thus the impact on the assessments of RE would likely be negligible. In addition, as multiple stages below lactate threshold are often surplus to diagnostic physiological assessments, the analysis of validity in Chapter 4 was confined to only 4 stages below LTP. A wider range of running speeds would have likely strengthened the comparisons between E_C and O_C, and thus provide a more comprehensive assessment of the validity of these measures.

Finally, the differences in methodology between the Chapters should be acknowledged. The method defined by Thoden et al. (1991) provided the primary calculation of LTP within this thesis. However, due to the retrospective nature of Chapter 4 and 6, the modified Dmax method was employed to calculate LTP as it provided a more robust and consistent method to calculate this variable across a large group where the number of stages completed, and the competitive distances of athletes, were highly variable. In addition, as Chapter 3 was completed prior to Chapter 4, a different scaling exponent is used to account for body mass when quantifying running economy. Although Chapter 4 revealed BM^{-1} to be more appropriate than the $BM^{-0.75}$ proposed by previous investigations in this area, it should be noted that inter-individual comparisons in Chapter 3 were limited, thus this differing method to account for body mass would have had a negligible impact on the results presented.

8.4 Future directions

It is clear that a greater exploration of the primary physiological determinants of an athlete's RE is required. Though previous cross sectional investigations have reported many physiological factors to be associated with RE (Williams and Cavanagh 1987a; Pate et al. 1992; Hunter et al. 2005), the relative contribution of these variables to the overall variance is often omitted. Without knowledge of the major determining factors of RE, the ability to diagnose specific inefficiencies within an athlete's characteristics and implement appropriate training interventions is severely limited. A comprehensive cross sectional investigation exploring commonly cited key variables, including tendon stiffness (Spurrs et al. 2003; Saunders et al. 2006; Arampatzis et al. 2006; Fletcher et al. 2010; Fletcher et al. 2013), mass distribution of the lower limbs (Larsen 2003; Lucia et al. 2006; Foster and Lucia 2007; Kong and Heer 2008; Lucia et al. 2008) and muscle fibre type composition (Costill et al. 1976; Bosco et al. 1987; Kaneko 1990; Hunter et al. 2001), in a large cohort of runners with multiple regression analysis could begin to elucidate the primary determinants of RE. Following this, investigations should confirm the findings by manipulating these variables with appropriate long-term interventions, and assessing the impact on RE and, crucially, performance.

8.5 Conclusion

The work contained in this thesis demonstrates that energy cost, appropriately scaled to body mass, provides a reliable and valid measurement of running economy for use in both empirical and applied settings. This work has also furthered the understanding of RE in highly trained runners, comprehensively demonstrating a limited association between running economy and maximal oxygen uptake in highly trained distance runners, and also a disparity in the magnitude of energy cost responses in the transition to uphill or downhill running from flat running. Finally, this thesis has provided the first insight into the physiological responses to structured downhill training, showing no improvements in running economy following an 8-week intervention in highly trained runners. It is proposed that future investigations should be directed towards the identification of the primary determinants of running economy, which would in turn develop our understanding of the trainability and performance impact of RE.

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