The Utility of Strength-Based Exercise for Middle- and Long-Distance Runners

Richard C Blagrove

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The Utility of Strength-Based Exercise for Middle- and Long-Distance Runners

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A thesis submitted in partial fulfilment of the requirements for the award Doctor of Philosophy of the University of Northumbria at Newcastle.

No part of this thesis has been submitted in the past, or is to be submitted for any degree at any other University.

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In memory of Lucy Pygott

ABSTRACT

Middle- and long-distance running performance is constrained by the complex interaction of physiological, biomechanical and neuromuscular factors. Several of these factors have the potential to be enhanced both acutely and chronically using strength-based exercise. A plethora of research has investigated the efficacy of strength training (ST) activities for improving physiological determinants of performance via enhancements in neuromuscular- and tendon-related properties. This body of literature has previously not been reviewed, nor is it known the extent to which the distance running community engage with ST. Moreover, research is specifically lacking in the post-pubertal adolescent age group and very few works have considered whether strength-based exercise could acutely potentiate performance-related outcomes.

The first aim of this thesis was to systematically review the literature on ST for distance runners. Based upon findings from 26 studies, it was evident that ST activities have the capability of improving time-trial performance, running economy (RE) and important anaerobic qualities following a 6-14 week intervention. Despite these findings, it is uncertain what proportion of runners include ST in their routine, and whether runners of a specific age and competitive status are more likely to participate.

The second study of this thesis aimed to explore ST practices of competitive distance runners (n=667). The most common activities utilised were stretching (86.2%) and core stability exercises (70.2%), despite limited evidence for their value. Resistance training and plyometric training (PT) were used by 62.5% and 35.1% of runners respectively. A disproportionately high number of under-17 and under-20 year old runners included PT, running drills and circuit training in their training, compared to older age groups. Indeed, ST is recommended for adolescent athletes to develop a wide-range of physical competencies, lower injury risk and enhance performance.

A test-retest reliability investigation was conducted (Study 3) in a group of adolescent distance runners, to ascertain the reproducibility of a range of important physiological and biomechanical variables related to distance running performance and strength outcomes. Following allometric scaling of variables influenced by body mass, reliability indices showed a high level of reproducibility across all physiological parameters and maximal speed (typical error $\leq$ 2%; intra-class correlation coefficient > 0.8; effect size (ES) < 0.6). Biomechanical metrics displayed moderate levels of inter-session consistency. Minimal detectable change values (95% confidence) were calculated to provide a robust threshold for identifying magnitude based inference terms in subsequent studies.

Study 4 investigated the effect of a ten week ST programme on a group of post-pubertal adolescent distance runners. Participants were randomly assigned to a group that added two weekly ST sessions to their training, or a control group, who continued their normal running. ST enhanced RE by a small

extent (ES: 0.31-0.51) and was highly likely to improve maximal speed without deleterious effects on body composition and other aerobic parameters.

The final study of this thesis investigated the efficacy of a short bout of strength-based exercise on physiological parameters and time to exhaustion (TTE) in a group of high-performing adolescent runners. Seventeen young male distance runners performed a baseline assessment session followed by two identical trials organised in a randomised crossover design. Prior to each trial, participants completed either six depth jumps (DJ) or a control condition. The DJ condition produced moderate significant improvements (-3.7%, $p<0.05$, ES: 0.67) in RE, which was considered 'possibly beneficial'. A small individual response was evident, which may in part be mediated by explosive strength status. TTE and other physiological variables were unaffected (ES: <0.2, $p>0.05$).

In conclusion, the addition of ST to the training routine of a middle- or long-distance runner appears to provide a performance advantage via improvements in RE and anaerobic factors. Despite these well-established benefits of ST, competitive runners tend to prefer other non-running based training techniques under the impression they lower injury risk and improve performance. Importantly, results from studies 4 and 5 in this thesis have shown that in the post-pubertal adolescent age-group, both chronic (ten week) and acute strength-based exercise interventions provide a small to moderate but possibly beneficial effect on RE.

Publications and conference proceedings arising from this thesis

Journal Publications

Blagrove, R. C., Howatson, G. and Hayes, P. R. (2018) Effects of strength training on the physiological determinants of middle- and long-distance running performance: a systematic review. *Sports Medicine,* 48(5), pp. 1117-1149.

Blagrove, R. C., Howatson, G. and Hayes, P. R. (2018) Use of loaded conditioning activities to potentiate middle- and long-distance performance: a narrative review and practical applications. *The Journal of Strength and Conditioning Research.* Published ahead of print. Doi: 10.1519/JSC.0000000000002456

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Blagrove, R. C., Howe, L. P., Cushion, E. J., Spence, A., Howatson, G., Pedlar, C. R. and Hayes, P. R. (2018) Effects of strength training on postpubertal adolescent distance runners. *Medicine and Science in Sports and Exercise,* 50(6), pp. 1224-1232.

Blagrove, R. C., Holding, K. M., Patterson, S. D., Howatson, G. and Hayes, P. R. (2018) Efficacy of depth jumps to elicit a post-activation performance enhancement in junior endurance runners. *Journal of Science and Medicine in Sport*. Published ahead of print. Doi: 10.1016/j.jsams.2018.07.023.

Blagrove, R. C., Howe, L. P., Howatson, G. and Hayes, P. R. (2018) Strength and conditioning for adolescent endurance runners. *Strength and Conditioning Journal*. Doi: 10.1519/SSC.0000000000000425

Commentary

Blagrove, R. C., Howatson, G. and Hayes, P. R. (2018) Quantification of exercise intensity as energy expenditure: reliability and units of measurement. Comment on: Beck, O.N., Kipp, S., Byrnes, W.C., Kram, R. Viewpoint: Use aerobic energy expenditure instead of oxygen uptake to quantify exercise intensity and predict endurance performance. *Journal of Applied Physiology*, In press for August 2018.

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Blagrove, R. C., Howe, L. P., Cushion, E. J., Spence, A., Howatson, G., Pedlar, C. R. and Hayes, P. R. (2016) Strength training enhances running economy in adolescent middle-distance runners. *British Association of Sport and Exercise Science Annual Conference*, East Midlands Conference Centre, UK, 29th – 30th Nov 2016.

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Strength and Conditioning Association Annual Conference, Hinkley Island, Leicestershire UK, 5th-6th August 2017.

Invited Conference Presentations

The World Endurance Summit, online international conference, USA, 27th November 2017. *A guide to strength training for endurance runners*.

The Movement Conference, St Mary's Stadium, Southampton, UK, 24th-25th March 2018. *Movement and physical preparation strategies for the distance runner.*

Marathon Medicine, The Royal Institute of British Architects, London**,** UK, 21st April, 2018. *The strength to last the distance: physical preparation of the long-distance runner.*

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LIST OF ABBREVIATIONS

The following abbreviations have been defined in the text in the first instance:

AMPK	Adenosine monophosphate activated kinase
ANCOVA	Analysis of covariance
BL	Blood lactate
CG	Control group
CI	Confidence interval
CMJ	Counter-movement jump
DJ	Depth jumps
EMG	Electromyography
ERT	Explosive resistance training
ES	Effect size
HR	Heart rate
HRT	Heavy resistance training
ICC	Intra-class correlation coefficient
iEMG	Integrated electromyography
IRR	Inter-rater reliability
LCA	Loaded conditioning activity
LT	Lactate threshold
LTP	Lactate turnpoint
MBI	Magnitude based inference
MDC	Minimal detectable change
MDC_{95}	Minimal detectable change for 95% confidence interval
MHC	Myosin heavy chain
MLC	Myosin light chains
mTOR	Mammalian target of Rapamycin
MVC	Maximum voluntary contraction
OR	Odds ratio
PAP	Post-activation potentiation
PEDro	Physiotherapy evidence database
Pl-3k	Phosphoinositide-3-dependent kinase
PT	Plyometric training
RE	Running economy
RER	Respiratory exchange ratio
RFD	Rate of force development
RM	Repetition maximum

RPE	Rating of perceived exertion
RT	Resistance training
SD	Standard deviation
sFBLC	Speed at fixed blood lactate concentration
sLTP	Speed at lactate turnpoint
sMART	Speed achieved during a maximal anaerobic running test
SpT	Sprint training
ST	Strength training
s$\dot{V}O_{2max}$	Speed associated with maximal oxygen uptake
SWC	Smallest worthwhile change
S&C	Strength and conditioning
TE	Typical error
TT	Time-trial
TTE	Time to exhaustion
$\dot{V}CO_2$	Volume of expired carbon dioxide
$vGRF_{jump}$	Peak vertical ground reaction force during concentric phase of a squat jump
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake during a maximal test

Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the Ethics and Research Committee at St Mary's University.

I declare that the Word Count of this Thesis is 58,468 words.

Name: Richard Blagrove

Signature:

Date: 18/04/2018

CHAPTER 1

INTRODUCTION

Running is one of the purest forms of human locomotion and is the most popular sports-related physical activity in England (Audickas, 2017). The aim for most competitive distance runners is to complete a race distance in as short a time as possible. Performance in middle- (0.8 – 3 km) and long-distance (5 – 42.2 km) running is limited by a complex interplay of intrinsic and extrinsic factors. Of the intrinsic factors, physiological, anthropometric and biomechanical variables are all known to contribute to performance outcomes. From a physiological perspective, the 'classical' model (di Prampero et al., 1986; Joyner, 1991; Sparling, 1984) identifies three main parameters, which largely influence long-distance running performance: maximal oxygen uptake ($\dot{V}O_{2max}$), running economy (RE), and fractional utilisation (sustainable percentage of $\dot{V}O_{2max}$). Additionally, speed at $\dot{V}O_{2max}$ (s$\dot{V}O_{2max}$) provides a composite measure of $\dot{V}O_{2max}$ and RE, and has been used to explain differences in performance amongst trained distance runners (Billat and Koralsztein, 1996). A strong relationship between blood lactate (BL) parameters and distance running performance has also been reported in adult runners (Fay et al., 1989; Grant et al., 1997).

Whilst $\dot{V}O_{2max}$ values differ little in homogenous groups of distance runners, RE displays a high degree of inter-individual variability (Conley and Krahenbuhl, 1980; Morgan and Craib, 1992). In well-trained distance runners, RE and $\dot{V}O_{2max}$ also appear to be largely unrelated qualities (Shaw et al., 2015), suggesting that each contribute independently to performance for different individuals. Defined as the oxygen or energy cost of sustaining a given sub-maximal running speed, RE is underpinned by a variety of anthropometric, physiological, biomechanical and neuromuscular factors (Barnes and Kilding, 2015a; Saunders et al., 2004a). Traditionally, chronic periods of running training have been used to enhance RE (Jones and Carter, 2000; Svedenhag and Sjodin, 1985), however novel approaches such as strength training (ST) modalities have also been shown to elicit improvements following a 6-14 week intervention period (Balsalobre-Fernandez et al., 2016; Denadai et al., 2017).

For middle-distance runners, cardiovascular-related parameters associated with aerobic energy production can explain a large proportion of the variance in performance (Abe et al., 1998; Brandon, 1995; Brandon and Boileau, 1992; Ingham et al., 2008; Lacour et al., 1990b; Padilla et al., 1992; Rabadan et al., 2011). However a large contribution is also derived from anaerobic sources of energy (Brandon, 1995; Busso and Chatagnon, 2006). Anaerobic capabilities can explain differences in physiological profiles between middle- and longer-distance runners (Brandon, 1995) and are more sensitive to discriminating performance in groups of elite middle-distance runners than traditional aerobic parameters (Paavolainen et al., 2000). Anaerobic capacity and event specific determinants, such as s$\dot{V}O_{2max}$ and the speed achieved during a maximal anaerobic running test (sMART), have also been proposed as limiting factors for distance runners (Billat et al., 1994; Brandon and Boileau, 1992; Houmard et al., 1991).

Both RE and anaerobic factors (speed, anaerobic capacity and sMART) rely on the generation of rapid force during ground contact when running (Beattie et al., 2014; Moore, 2016). Programs of ST provide an overload stimulus to the neuromuscular system, which improves motor unit recruitment, firing frequency, musculotendinous stiffness and intra-muscular co-ordination, and therefore potentially provides distance runners with a strategy to enhance their RE and event-specific determinants (Paavolainen et al., 2000). In addition, an improvement in force-generating capacity would theoretically allow athletes to sustain a lower percentage of maximal strength, thereby reducing anaerobic energy contribution (Fletcher and MacIntosh, 2017). This reduction in relative effort may therefore enhance RE and BL concentration. As s$\dot{V}O_{2max}$ is a function of RE, $\dot{V}O_{2max}$ and anaerobic factors, it would also be expected to show improvements following a ST intervention. Several recent reviews in this area have provided compelling evidence that a short-term ST intervention is likely to enhance RE (Balsalobre-Fernandez et al., 2016; Berryman et al., 2017; Denadai et al., 2017) in the order of ~4% (Denadai et al., 2017). Whilst these reviews have provided valuable insight into how ST specifically impacts RE, studies also typically measure other important aerobic and anaerobic determinants of distance running performance, which have not previously been fully synthesised in a review. Body composition also appears to be an important determinant of distance running performance, with low body mass conferring an advantage (Cavanagh et al., 1977; Coetzer et al., 1993). Resistance training (RT) is generally associated with a hypertrophic response (Schoenfeld et al., 2016), however this is known to be attenuated when lower limb RT and endurance running training are performed concurrently within the same programme (Wilson et al., 2012b). Changes in body composition as a consequence of ST in distance runners have yet to be fully addressed in reviews on this topic.

There are also a number of recent publications (Beattie et al., 2017; Clark et al., 2017; Denadai and Greco, 2017b; Giovanelli et al., 2017; Karsten et al., 2016; Stohanzl et al., 2017; Vikmoen et al., 2016; Vikmoen et al., 2017) that have not been captured in previous reviews (Balsalobre-Fernandez et al., 2016; Denadai et al., 2017) on this topic, which potentially provide valuable additional insight into the area. Previous papers, which have reviewed the impact of ST modalities on distance running performance, have done so alongside other endurance sports (Beattie et al., 2014; Berryman et al., 2017) or are somewhat outdated (Jung, 2003; Tanaka and Swensen, 1998; Yamamoto et al., 2008). Furthermore, although improvements in RE would likely confer a benefit to distance running performance, the outcomes from studies which have used a time trial (TT) have not been comprehensively reviewed. Performance-related outcome measures provide high levels of external validity compared to physiological parameters, therefore it is likely that a collective summary of results would be of considerable interest to coaches and athletes.

Despite the seemingly large body of literature that has investigated the impact of ST on parameters relating to distance running, very little is known about the extent to which runners are incorporating such activities into their training programme. Previous research has documented the training practices of distance runners (Bale et al., 1985; Hewson and Hopkins, 1995; Karp, 2007; Knechtle et al., 2011; Voight et al., 2011), however very few studies mention the degree to which ST activities are included. Such information could be used to understand the impact of the current scientific knowledge and influence the development of professional coaching courses and programmes of education for the coaches of athletes, as well as shape the direction of the present thesis.

There is convincing evidence that programmes of ST exercise are safe and effective for young athletes (Behringer et al., 2011; Harries et al., 2012), and may offset the risk of injury (Myer et al., 2011). Studies on ST in youth populations have tended to focus on the development of strength-related qualities, which underpin a variety of different sports skills (Faigenbaum et al., 2016; Harries et al., 2012). Current guidelines suggest that adolescents should participate in 2-3 ST sessions per week, which are supervised by appropriately qualified personnel (Lloyd et al., 2014; Myer and Wall, 2006).

Approximately a quarter of 11-15 year olds participate regularly in cross-country, jogging or road running activities in the UK (DCMS, 2016) and endurance running represented the second most popular sport (18.7%) in a survey (*n*=7794) of Scandanavian 14 year olds (Tammelin et al., 2003). Despite the abundance of research that has investigated the effect of ST on adult distance runners, there is a dearth of knowledge on adolescent runners. The results of research in this important age-group would potentially be highly useful, as any positive outcomes in terms of performance-related improvement would provide a compelling message for adolescent runners, their parents and coaches, who potentially hold concerns surrounding the use of such activities in young athletes (Stone et al., 2014).

Acute improvements in distance running performance and related physiological factors using various pre-performance ergogenic strategies are also an area which has been explored (Bailey et al., 2012; Barnes et al., 2015; Ingham et al., 2013; Jones et al., 2003a; Kressler et al., 2011; Murphy et al., 2012; Stellingwerff, 2013). The use of a short bout of strength-based exercise, termed a ‘loaded conditioning activity’ (LCA), in the warm-up routine of athletes has been investigated extensively for short duration explosive activities such as jumps and sprints, generally showing improvements in performance (Maloney et al., 2014; Seitz and Haff, 2016; Wilson et al., 2013). The improvements have been attributed to the ‘post-activation potentiation’ (PAP) phenomena which is associated with a short-term enhancement in neuromuscular performance as a result of a muscle’s prior contractile history (Tillin and Bishop, 2009). Several mechanisms are thought to explain a PAP response, including phosphorylation of myosin light chains (MLC), which increases the sensitivity of calcium ions at a molecular level (MacIntosh, 2010), recruitment of higher order motor units (Tillin and Bishop, 2009), and enhanced musculotendinous stiffness (Maloney et al., 2014). Although individuals who possess a greater proportion of type II muscle fibres (Vandervoort et al., 1983) and well-trained performers (Seitz and Haff, 2016) are more likely to gain a benefit from a LCA, previous research has shown a potentiation response is possible in endurance-trained individuals (Hamada et al., 2000; Morana and Perrey, 2009). Despite this finding, very little research has been conducted experimentally to examine whether an improvement in distance running performance is possible following an LCA. A group of young highly-trained middle-distance runners represent a group of endurance athletes who are perhaps most likely to experience an improvement in performance-related measures following a LCA, as it is probable they will have a higher percentage of type II muscle fibres compared to their long-distance adult counterparts (Larsson and Karlsson, 1978).

1.1 Aims of Thesis

Research investigating the impact of ST on distance runners is extensive, yet these findings have previously not been reviewed for all physiological factors that contribute to performance. Despite a consensus in the scientific literature concerning the chronic benefits of ST on RE, it is currently uncertain whether competitive runners incorporate strength and conditioning (S&C) related activities into their training. The post-pubertal period represents a crucial time, where athletes typically elect to specialise in a single sport and performance inevitably improves rapidly (Brenner, 2016; Myer et al., 2015). There is also compelling evidence that ST activities are beneficial to adolescent athletes, however there is a lack of literature specifically in young distance runners. Strategic manipulation of warm-up activities to gain a short-term performance advantage has also received considerable research attention, specifically for power-based athletes. To-date there have been virtually no studies that have examined whether an acute bout of strength-based exercise can improve physiological parameters related to distance running performance.

Based upon this current understanding, the overall aim of this thesis was to examine the utility of strength-based exercise for distance runners, with a focus on the post-pubertal adolescent age-group. This aim was addressed over the course of five specific studies, which were as follows:

1. Investigate the efficacy of ST modalities on the physiological determinants and performance of middle- and long-distance runners by conducting a systematic review (Study 1).
2. Describe the extent to which distance runners engage with ST activities and the characteristics of those who participate in various activities (Study 2).
3. Quantify the reliability of physiological and biomechanical markers relating to performance outcomes in adolescent distance runners (Study 3).
4. Examine the effect of a 10 week ST intervention on the physiological determinants of performance in post-pubertal adolescent distance runners (Study 4).
5. Evaluate the impact of including an LCA in a warm-up routine on physiological variables and time to exhaustion (TTE) in young male distance runners (Study 5).

CHAPTER 2

LITERATURE REVIEW

Published papers from this chapter:

Blagrove, R. C., Howatson, G. and Hayes, P. R. (2018) Effects of strength training on the physiological determinants of middle- and long-distance running performance: a systematic review. *Sports Medicine,* 48(5), pp. 1117-1149.

Blagrove, R. C., Howatson, G. and Hayes, P. R. (2018) Use of loaded conditioning activities to potentiate middle- and long-distance performance: a narrative review and practical applications. *The Journal of Strength and Conditioning Research.* Published ahead of print. Doi: 10.1519/JSC.0000000000002456

2.1 Introduction and Aims of Literature Review

It is traditionally viewed that distance running performance is limited by physiological factors associated with the cardiovascular and metabolic systems (Thompson, 2017) and is improved with extensive sub-maximal training (Seiler, 2010). Conversely, 'strength' refers to an individual's ability to apply force under a specified set of movement constraints (Goodwin and Cleather, 2016), which is principally underpinned by neuromuscular qualities. ST involves modalities of exercise that seek to improve the ability to express force under these circumstances (Zatsiorsky and Kraemer, 2006), such as RT, explosive resistance training (ERT) or ballistic training, and plyometric training (PT). It is apparent therefore that aerobic endurance training and ST sit at somewhat opposite ends of an adaptation continuum (Hawley, 2009). From a training specificity perspective, it may be expected that these disparate types of exercise offer little benefit to one another in terms of the outcomes that each aim to achieve.

The aims of this literature review are four-fold. Firstly, the physiological determinants of middle- and long-distance running performance are examined to enable identification of exercise interventions that have the potential to improve performance (Sections 2.2 - 2.4). Secondly, and relating to Study 1 of the thesis, a systematic review is conducted, which investigates the efficacy of ST on the physiological determinants and performance of distance runners (Section 2.5). Thirdly, the acute impact of a short bout of strength-based exercise, or an LCA, on outcomes relating to endurance performance are explored from a mechanistic and evidenced-based perspective (Section 2.6). Finally, a brief overview of the literature that has addressed youth athlete development and the effects of ST on adolescent populations is also included (section 2.7).

2.2 Deterministic Models of Middle- and Long-Distance Running Performance

Outside of actual race performances, which can be influenced by a variety of exogenous factors, a time-trial (TT) represents the gold standard measure of performance (Currell and Jeukendrup, 2008). Despite the high level of ecological validity associated with TT performance, internal validity can be questionable due to confounding factors such as pacing, drafting of other participants, motivation, and environmental conditions if performed outdoors. To ameliorate several of these limitations, some investigators advocate the use of TTE tests at an intensity that closely resembles the competitive event as a proxy of performance (Hopkins et al., 2001), although this approach has also been recently been criticised for lacking relevance (Dankel et al., 2017b).

Several physiological markers have been identified as being highly associated with middle- and long-distance running performance (Bassett and Howley, 2000; Brandon and Boileau, 1992; Conley and Krahenbuhl, 1980; Coyle, 1995; Denadai et al., 2004; Joyner, 1991; Joyner and Coyle, 2008; McLaughlin et al., 2010; Sparling, 1984). Measurement of these variables in a tightly controlled laboratory environment allows scientists to further understand the factors that underpin successful distance running performance and retain high levels of construct validity (Currell and Jeukendrup, 2008). Bassett and Howley (2000) provide a summary of the major determinants of endurance running performance (see Figure 2.1), which is widely recognised at the ‘classical’ model (Bassett and Howley, 1997; di Prampero et al., 1986; Joyner, 1991; Sparling, 1984). $\dot{V}O_{2max}$ represents the upper limit for the rate of aerobic metabolism, with the lactate threshold (LT) corresponding to the fraction of $\dot{V}O_{2max}$ that can be sustained (%$\dot{V}O_{2max}$ at LT) for a given distance. Running performance is subsequently determined by how much energy is utilised (RE) at the fractional utilisation of $\dot{V}O_{2max}$. Collectively, these determinants are capable of predicting 16 km performance with more than 95% accuracy in well-trained runners (McLaughlin et al., 2010).

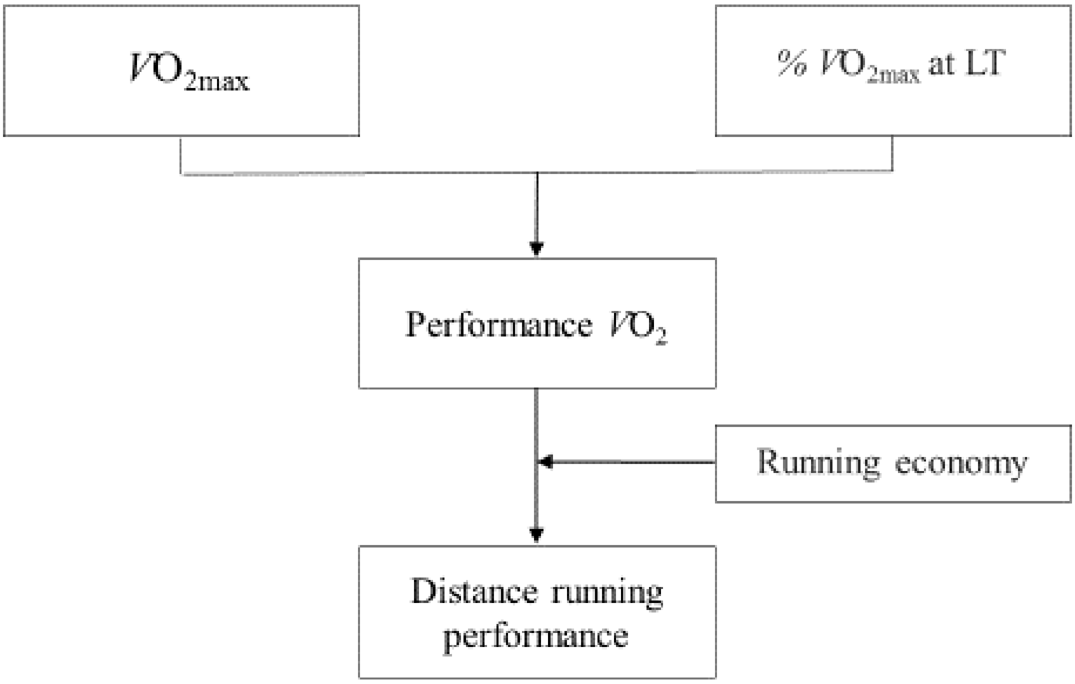


Figure 2.1. The ‘classical’ model of distance running providing a summary of main determinants influencing performance (Joyner, 1991; Taken from: Bassett and Howley, 2000). $\dot{V}O_{2max}$ = maximal oxygen uptake, LT = lactate threshold

These determinants described by the classical model have also been identified as important predictors of middle-distance running performance (Abe et al., 1998; Brandon and Boileau, 1992; Ingham et al., 2008; Lacour et al., 1990b; Rabadan et al., 2011). Ingham and colleagues (2008) were able to explain 96% of inter-individual variability using only $\dot{V}O_{2max}$ and RE as predictors of performance in 62 national and international 800/1500 m runners. Aerobic-based qualities are clearly a necessity for the middle-distance events, however the relative importance of the factors described in the classical model are different between middle- and long-distance runners (Thompson, 2017). Owing to the higher speeds exhibited in middle-distance events, energy requirements far exceed that which can be provided via aerobic metabolism (Brandon, 1995). Anaerobic capabilities, such as those identified in Figure 2.2, are therefore necessary for success in middle-distance events, thus runners are less dependent upon aerobic determinants for success (Brandon, 1995; Houmard et al., 1991).

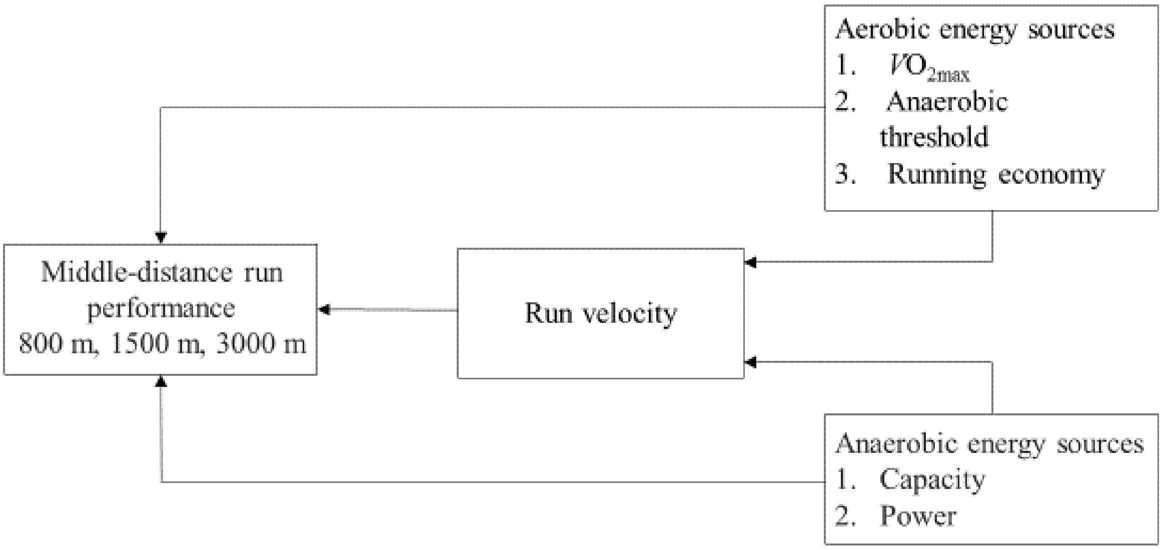


Figure 2.2. Physiological determinants model for middle-distance running (Brandon, 1995). $\dot{V}O_{2max}$ = maximal oxygen uptake.

Since direct measurement of running-related anaerobic capabilities is problematic, studies have used indirect assessments of ‘endurance specific muscular power’ (Billat and Koralsztein, 1996; Houmard et al., 1991; Paavolainen et al., 1999a; Paavolainen et al., 2000; Paavolainen et al., 1999b; Paavolainen et al., 1999c). The seminal paper by Paavolainen and co-workers (1999a) demonstrated that the addition of explosive ST (ERT and PT) to the programme of highly-trained distance runners for nine weeks produced superior improvements in 5 km TT performance, RE, sMART, jump and sprint performance. The same authors also demonstrated that sMART and 20 m sprint were able to accurately predict 5 km TT performance (Paavolainen et al., 1999c) and force-producing characteristics (ground-reaction force and pre-activation of gastrocnemius) were identified as important factors for 10 km performance (Paavolainen et al., 1999b). These investigations gave rise to an alternative deterministic model of distance running performance, which includes limiting factors relating to the neuromuscular system (Figure 2.3).

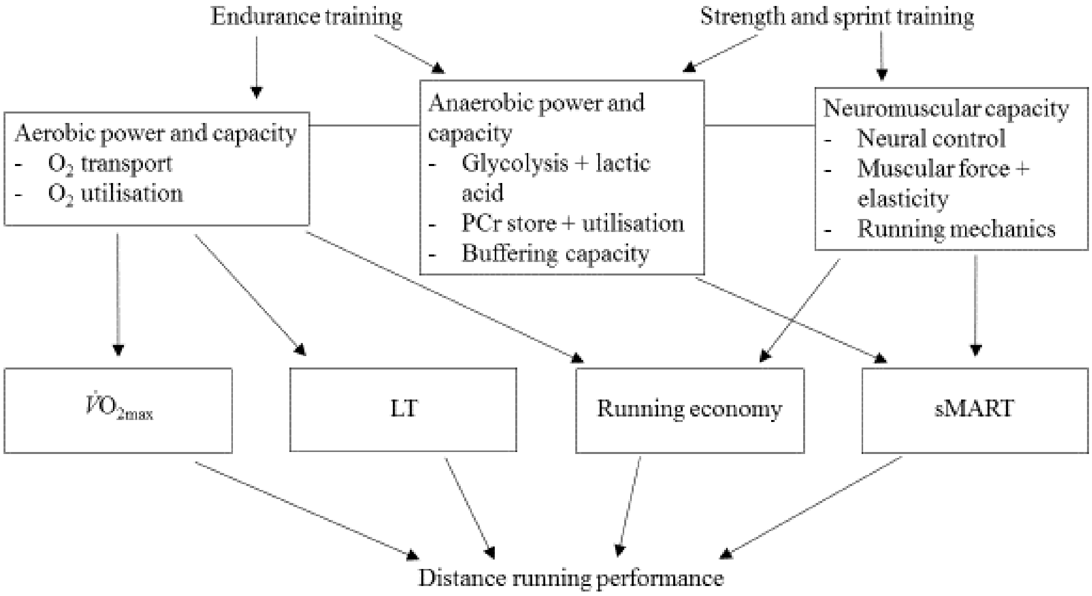


Figure 2.3. Determinants of distance running performance including both aerobic and neuromuscular influences (Paavolainen et al., 1999a). O_2 = oxygen, PCr = phosphocreatine, $\dot{V}O_{2max}$ = maximal oxygen uptake, LT = lactate threshold, sMART = speed achieved during a maximal anaerobic running test

2.3 Limitations to Performance and Strategies to Improve Determinants

2.3.1 Maximal Oxygen Uptake

It is well-established that $\dot{V}O_{2max}$ is a key determinant of both middle- (Brandon, 1995; Foster, 1983; Ingham et al., 2008) and long-distance running performance (Bassett and Howley, 2000; Foster, 1983) therefore the objective for any distance runner is to maximise their aerobic power (Jones and Carter, 2000). Elite standard male distance runners possess $\dot{V}O_{2max}$ values of 70-85 $mL \cdot kg^{-1} \cdot min^{-1}$ and their female counterparts 60-75 $mL \cdot kg^{-1} \cdot min^{-1}$ (Jones, 2006b; Svedenhag and Sjodin, 1985), which is typically 40-50% higher than age-matched sedentary controls (Wilmore and Costill, 1999). Although $\dot{V}O_{2max}$ is highly trainable, it is believed to have a strong genetic component (Bray et al., 2009). In highly-trained distance runners, $\dot{V}O_{2max}$ values are likely to be close to the genetic ceiling therefore tend to be similar and poor at explaining the inter-individual variability in performances (Allen et al., 1985; Conley and Krahenbuhl, 1980). Although a high $\dot{V}O_{2max}$ is considered a pre-requisite for high-standard distance running performance, other physiological factors must therefore provide a more accurate prediction of performance, particularly in homogenous groups of runners (Denadai et al., 2004; Morgan et al., 1989; Noakes et al., 1990). Indeed, case studies of the world-record holder for the women’s marathon (Jones, 2006b) and a former elite cyclist (Coyle, 2005) show $\dot{V}O_{2max}$

remained relatively stable over long periods of time (7-11 years), despite improvements in performance.

Both continuous training and high-intensity (90-100% $\dot{V}O_{2max}$) interval training elicit improvements in $\dot{V}O_{2max}$ following a 3-24 week training intervention (Milanovic et al., 2015). However there is a growing body of evidence that suggests high-intensity training provides a more potent stimulus to maximise adaptations long-term (Bacon et al., 2013; Gist et al., 2014), including in highly-trained endurance athletes (Kubukeli et al., 2002; Laursen and Jenkins, 2002). Therefore, it is perhaps likely that a combination of continuous and high-intensity running sessions yield the greatest benefit to $\dot{V}O_{2max}$ in the long-term (Seiler, 2010).

A summary of the physiological adaptations that underlie improvements in $\dot{V}O_{2max}$ as a consequence of endurance training are shown in Figure 2.4. The Fick equation defines that $\dot{V}O_{2max}$ is the product of maximal cardiac output (stroke volume x heart rate (HR)) and the difference in oxygen concentration between arterial and venous blood ($a - \bar{v}O_2$ diff). This suggests that adaptations underpinning an improvement in $\dot{V}O_{2max}$ could be a consequence of either central (oxygen delivery by cardiovascular system) or peripheral (oxygen extraction at muscular level) mechanisms (Levine, 2008). Central mechanisms relating to increases in blood volume, red blood cell mass and stroke volume largely explain inter-individual variability in $\dot{V}O_{2max}$ values and correlate well with improvements, particularly after periods of >12 weeks (Montero et al., 2015). Although theoretical models (Wagner, 2015) suggest improvements in $\dot{V}O_{2max}$ may be partly explained by peripheral factors such as augmented capilliarisation and increases in size and density of mitochondrial content, there is little experimental evidence indicating these mechanisms limit oxygen extraction. Theories surrounding a possible contribution to $\dot{V}O_{2max}$ improvement from motor unit recruitment have also been offered (Brink-Elfegoun et al., 2007; Hawkins et al., 2007) but have been largely dismissed (Levine, 2008; Lundby et al., 2017). Circulatory factors (total oxygen carrying capacity of blood) therefore appear to be the dominant factor underlying improvements in $\dot{V}O_{2max}$ (Lundby et al., 2017).

Conversely, ST is associated with a hypertrophy response that increases body mass and has been reported to decrease capillary density, oxidative enzymes and mitochondrial density (Dudley, 1988; Kraemer et al., 1996; Tesch et al., 1987), which should adversely impact aerobic performance. Theoretically there is therefore little basis for ST as a strategy to enhance aerobic power. However it is important to address as part of a systematic review whether in fact $\dot{V}O_{2max}$ is negatively affected when distance running is performed concurrently with ST (see Section 2.5).

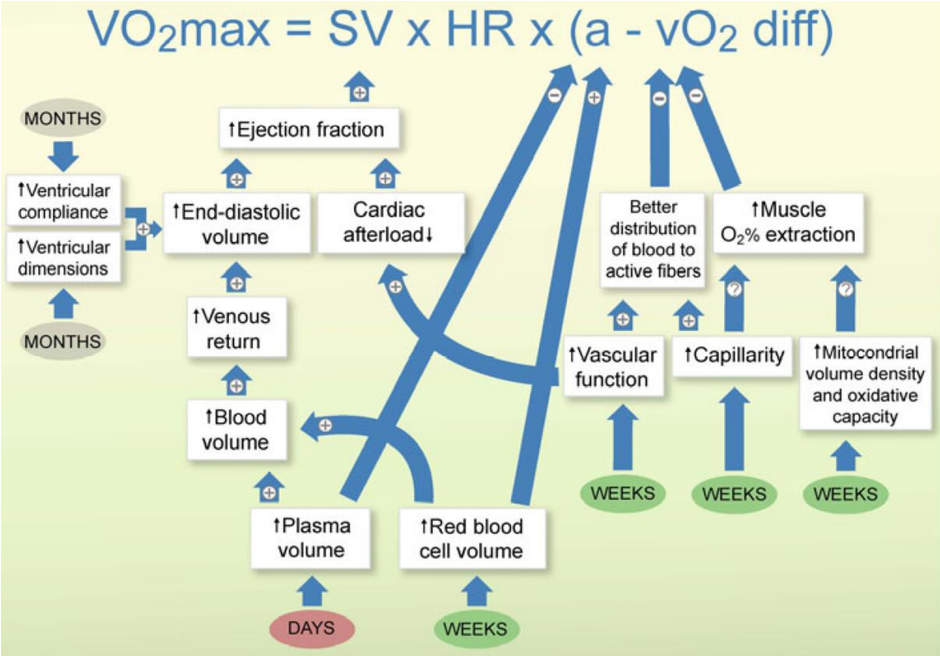


Figure 2.4. A summary of the physiological adaptations underpinning improvements in $\dot{V}O_{2max}$ with exercise training (Lunby et al., 2017). VO_2max = maximal oxygen uptake, SV = stroke volume, HR = heart rate, a – vO_2 diff = difference in oxygen concentration between arterial and venous blood, O_2 = oxygen.

2.3.2 Running Economy

Although $\dot{V}O_{2max}$ represents an important determinant of performance in a heterogeneous population of distance runners, RE, defined as the oxygen or energy cost to run at a given sub-maximal velocity, appears to be far better at distinguishing between differences in performance amongst populations with similar $\dot{V}O_{2max}$ scores (Conley and Krahenbuhl, 1980; Daniels, 1985; Ingham et al., 2008). As shown in the hypothetical example in Figure 2.5, an individual with good RE will use less oxygen (or energy) than a runner with poor economy for the same sub-maximal running speed, despite both individuals being matched for $\dot{V}O_{2max}$. In this regard, RE can compensate for possessing a low $\dot{V}O_{2max}$. Jones (2006) suggested a value of 200 $mL{\cdot}kg^{-1}{\cdot}km^{-1}$ is considered average for a distance runner. Inter-individual variation in RE can be as high as 30% in groups of runners homogenous for $\dot{V}O_{2max}$, and improvements in RE appear to be closely related to performance improvements (Beneke and HÜtler, 2005; Coyle, 2005; Hoogkamer et al., 2016; Jones, 2006b; Saunders et al., 2010). The dominance of East African distance runners on the international-stage, who are reported to possess superior RE compared to their European and North American counterparts (Larsen and Sheel, 2015; Wilber and Pitsiladis, 2012), is also likely to have spawned the interest in RE as a determinant of real significance to distance running performance. Whilst RE is fairly simple to measure in a laboratory setting, the factors underpinning its manifestation are a reflection of a complex interaction between several physiological systems (Figure 2.6). Many of the factors affecting RE can be modified with the use of training interventions. Factors that are non-modifiable or cannot be easily controlled, such as anthropometric variables and environmental conditions, will not be discussed as part of this review.

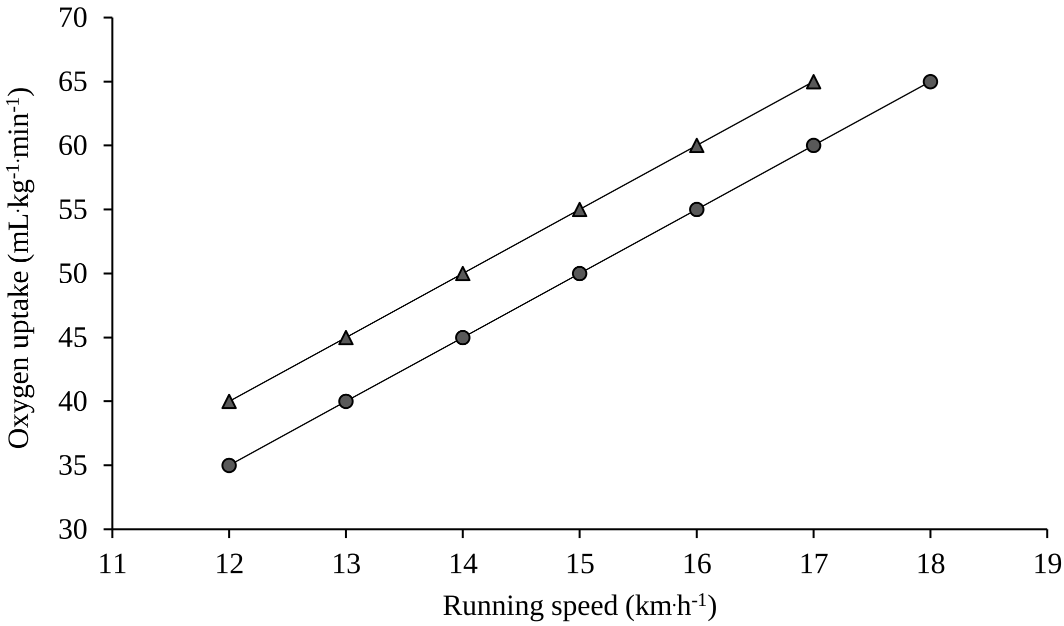


Figure 2.5. Hypothetical example of how two runners with the same maximal oxygen uptake ($\dot{V}O_{2max}$) may differ in terms of their running economy and speed at $\dot{V}O_{2max}$, which is a product of both physiological determinants.

2.3.2.1 Physiological Mechanisms

Cardiorespiratory mechanisms associated with breathing and HR may be partly responsible for the energy cost associated with exercise. Minute ventilation values during sub-maximal exercise have been suggested to contribute 6-7% of the overall energy requirement (Milic-Emili et al., 1962), and a relationship has previously been reported for changes in minute ventilation and improvements in RE following a running training intervention (Franch et al., 1998). If respiratory physiology is improved via training this may therefore contribute to an enhancement in RE. Although HR is positively correlated with RE (Pate et al., 1992), it is unlikely that reduced myocardial $\dot{V}O_2$ makes a significant contribution to lower RE values (Bailey and Pate, 1991).

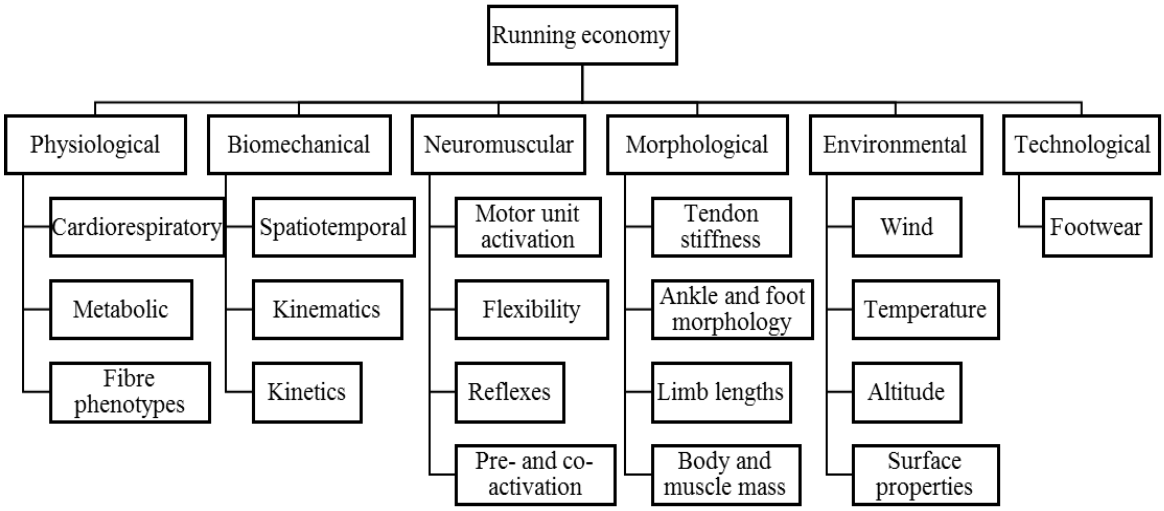


Figure 2.6. Factors underpinning running economy as potential avenues for enhancement (Barnes and Kilding, 2015a; Barnes and Kilding, 2015b; Fletcher and MacIntosh, 2017; Moore, 2016)

Continuous running (Beneke and HÜtler, 2005; Moore et al., 2012) and interval training (Barnes et al., 2013a; Denadai et al., 2006; Franch et al., 1998) have been shown to enhance RE via adaptations relating to improvements in oxygen delivery and utilisation within the muscle cell. Specifically, an increase in mitochondrial density, haematological variables and buffering capacity have been noted following endurance training interventions (Blomqvist and Saltin, 1983; Holloszy and Coyle, 1984) and these changes enable runners to utilise less energy for a given sub-maximal speed. Several authors have suggested that endurance training history is an important factor determining superior RE (Mayhew et al., 1979; Midgley et al., 2007a; Morgan et al., 1995; Nelson and Gregor, 1976). For example, Mayhew and colleagues (1979) found a significant relationship ($r = 0.62$) between years of training and RE, and case reports have demonstrated continued improvement in RE over long periods of time (Conley et al., 1984; Daniels, 1974; Ingham et al., 2012; Jones, 2006b). Recreational runners have also been shown to possess higher stride-to-stride movement variability, more inconsistent muscle recruitment patterns and longer durations of muscle activity compared to moderately-trained runners (Chapman et al., 2008). These factors suggest an inferior level of motor control in lesser trained runners, which is in line with findings from across the motor learning literature showing that long-term practice of a skill decreases movement variability, and results in reduced amplitude and duration of muscle activity, thus improving economy (Osu et al., 2002; Thoroughman and Shadmehr, 1999).

Skeletal muscles are composed of fibres that possess a range of metabolic and contractile characteristics (Zierath and Hawley, 2004) that are likely to influence RE (Morgan and Craib, 1992). Fibres are commonly classified according to their physiological properties as type I, type IIa or type IIx. Type I are generally found in higher proportions in successful endurance athletes (Costill et al., 1976b; Saltin et al., 1977) and possess functional characteristics that should positively influence RE, however evidence for a relationship between fibre type and RE is mixed (Bosco et al., 1987; Kyrolainen et al., 2003). Skeletal muscles demonstrate plasticity, which allows them to adapt over time to the contractile activity and loading they are exposed to (Zierath and Hawley, 2004). Long-term exposure to low-intensity endurance training has shown that type II fibres can take on many of the characteristics of type I fibres (mitochondrial density, oxidative enzymes, capillary density, ATPase activity) (Taylor and Bachman, 1999; Widrick et al., 1996), which may also contribute to an improved RE.

Long-distance runners tend to be shorter and lighter than middle-distance runners (Cavanagh et al., 1977) and one of the principal reasons cited for the success of East African distance runners is their low body mass compared to Caucasian runners (Larsen and Sheel, 2015; Wilber and Pitsiladis, 2012). Carrying metabolically inactive tissue such as excess body fat or muscle elevates RE since a greater level of absolute force is required to overcome gravity, which demands a higher level of muscle activation (Keller et al., 1996; Taylor et al., 1980). Reducing body fat via exercise and nutritional interventions is therefore an effective strategy to improve RE.

Chronic periods of RT are likely to produce a hypertrophic response, which increases muscle cross-sectional area (Schoenfeld, 2010). Intuitively this may appear to be a negative consequence for a distance runner. However if the increase in muscle size contributes towards an improvement in force generating ability during the stance phase of running, this would theoretically result in a lower relative intensity, reducing the need for recruitment of higher threshold motor units, which are associated with high rates of energy usage (Fletcher and Macintosh, 2017). It has recently been questioned whether an increase in muscle cross-sectional area is a mechanism at all for the improvements in force production observed following a RT intervention (Buckner et al., 2016; Dankel et al., 2018). It is important to recognise that if an increase in muscle cross-sectional area does not directly contribute towards enhancement of force production, the additional mass would negatively impact RE. Moreover, adding mass to distal regions of the lower limb (triceps surae) is more metabolically costly than adding mass to proximal muscle groups (gluteals) due to the additional cost associated with angular displacement of a heavier swinging limb during the recovery phase of gait (Jones et al., 1986).

2.3.2.2 Musculotendinous Mechanisms

It has recently been suggested that the energy cost associated with active skeletal muscle contraction represents the majority of the metabolic cost associated with sub-maximal running (Fletcher and MacIntosh, 2015). The amount of energy required for a muscle to contract during running is dependent upon the force required, duration of contraction, length-tension and force-velocity needed to move a limb through a specific angular displacement (Fletcher and MacIntosh, 2017). For any given running speed, force production (impulse) is predominantly required to overcome the acceleration due to gravity. Therefore as running speed increases and less time is available to generate force on the ground, the demand for producing force quickly increases (Weyand et al., 2000). RE therefore tends to increase as a function of speed because higher peak forces are required in shorter time frames, thus greater levels of muscle activation are needed (Keller et al., 1996; Kram and Taylor, 1990). If target force can be developed isometrically, motor unit activation will be minimised (Chow and Darling, 1999) and thus energy cost will be low (Fletcher and MacIntosh, 2017). However, the force-velocity relationship dictates that if muscle shortening contributes to the achievement of a given target force, a greater level of muscle activation is required to maintain the required force and thus energy demand increases. Energy cost of running is therefore proportional to the contribution derived from concentric muscle actions and the velocity of these contractions. Although the early part of ground contact is likely to involve a lengthening muscle contractions, which are highly energy efficient, a subsequent shortening contraction is required to produce sufficient vertical force to overcome gravity. This is also likely to increase the volume of muscle recruited, as fascicle length increases the active cross-sectional area involved in force production (Roberts et al., 1998). Moreover, for a given amount of muscular force, energy cost will also be minimised if the muscle contracts at its optimal length (Gordon et al., 1966). Therefore if joint angular displacement during ground contact is high, energy cost is likely to be increased. It follows that if a runner has the capability to reduce muscle fibre shortening by achieving close to an isometric state rapidly during ground contact, this will minimise energy cost (Fletcher and MacIntosh, 2017). Muscle activation is achieved via a combination of motor unit recruitment and firing frequency (Fuglevand et al., 1993), therefore an improvement in these neural mechanisms via ST may lead to an improvement in RE.

In addition to the active components of the muscle-tendon unit, the series elastic component (tendons) will also be stretched during early ground contact, which momentarily stores potential strain energy that can subsequently be released to reduce energy cost. It has been estimated that tendons in the foot and ankle contribute 30-40% of the energy required to sustain running at a moderate speed (Cavagna et al., 1964; Ker et al., 1987). A simultaneous rapid lengthening of the muscle fibres would also stimulate muscle spindles, contained within specialised intrafusal fibres, to provide sensory feedback via Ia afferent neurons, initiating a monosynaptic reflexive response that increases subsequent concentric force output (Sinkjær et al., 1996).

Pre-activation of muscles immediately prior to foot strike is an important feature of stretch-shortening cycles and is thought to facilitate greater musculotendinous stiffness during running via tolerance of impact forces on landing (Kyrolainen et al., 2001). Higher levels of muscle activity have been associated with greater energy cost (Kyrolainen et al., 2001), however an increase in preparatory muscle activation prior to foot strike is likely to reduce overall energy cost if the initial muscle length change is of smaller magnitude and at a lower velocity (Abe et al., 2007).

It is believed that tendons behave in such a manner that seeks to optimise the length-tension and force-velocity of muscle fascicles to minimise energy cost (Fletcher et al., 2013; Ishikawa et al., 2007; Kawakami et al., 1998; Lutz and Rome, 1994). Theoretically, a more compliant tendon would be capable of storing and returning higher levels of energy (Fletcher and MacIntosh, 2017), however previous studies have shown that the most economical runners possess stiffer tendons (Arampatzis et al., 2006; Dalleau et al., 1998; Dumke et al., 2010; Rogers et al., 2017). This paradox can be explained by the fact that tendons operate primarily to optimise muscle force-length-velocity relationships thereby reducing energy cost (Fletcher and MacIntosh, 2017). The additional mechanical energy stored and released from tendons represents only a small reduction in total energy cost (Fletcher and MacIntosh, 2015; 2017; Ker et al., 1987), particularly when it is considered that a stiffer Achilles tendon actually stores less strain energy for any given force. In theory, a tendon with optimal stiffness is capable of accommodating all of the muscle-tendon unit length change during human running (Ishikawa et al., 2007; Lichtwark et al., 2007). The tendon would therefore provide the majority of energy for force generation from storage and return of elastic strain energy and allow muscles to work under isometric conditions, which minimises energy cost. This theory has been tested experimentally in both frogs (Holt et al., 2014; Lutz and Rome, 1994) and chickens (Gabaldón et al., 2008) and appears to occur. It should be noted that if a tendon is too stiff, muscle fibres will invariably be required to lengthen and shorten to cope with the impact forces at ground contact and there would be little opportunity for storage of strain energy. Therefore it has been suggested that an optimal stiffness exists for different running speeds that will minimise energy cost of running (Fletcher and MacIntosh, 2017). Various ST techniques have been shown to increase tendon stiffness (Fletcher et al., 2010; Kubo et al., 2001a; Kubo et al., 2002; Kubo et al., 2001b), therefore it seems likely ST may enhance RE. It is thought that alterations to the intra-cellular matrix (material properties) of tendons, rather than increases in cross-sectional area or resting tendon length, underpin increases in tendon stiffness following a RT or PT intervention (Bohm et al., 2015).

2.3.2.3 Biomechanical Mechanisms

A distance runners freely-chosen stride frequency and stride length correspond to the RE associated with the lowest RE, and trained runners are capable of adjusting their stride frequency in a fatigued state to optimise energy cost (Moore, 2016). However, based upon mathematical modelling it is thought that (on average) optimal stride frequency should be 3% faster and stride length 3% shorter for most trained runners (Cavanagh et al., 1977; Connick and Li, 2014; De Ruiter et al., 2014). For less trained runners, these values are thought to be further from the optimum (De Ruiter et al., 2014). Ground contact time reduces as running speed increase, however it is recognised that energy cost is proportional to the average vertical force during ground contact but inversely related to the ground contact time over which the force is applied (Fletcher and MacIntosh, 2017; Kram and Taylor, 1990). A higher stride frequency and shorter ground contact time would maximise the contribution from stored elastic energy, since less would be wasted as heat (Alexander, 1991). However, short ground contact time also increases the demand to generate force rapidly, therefore a higher level of muscle activation is required, which increases metabolic cost. Therefore, for a given running speed, there seems to be a trade-off, which favours a cadence slightly lower than optimal and longer ground contact time to optimise RE for each individual. This hypothesis is supported by several papers showing an inverse relationship between RE and ground contact time (Chapman et al., 2012; Di Michele and Merni, 2014; Williams and Cavanagh, 1987), although other studies have not confirmed this finding (Folland et al., 2017; Heise and Martin, 2001; Støren et al., 2011). Although longer ground contact times at a given sub-maximal speed appear to lower metabolic cost, it is also likely that excessively long contact times would produce a higher braking force (Moore et al., 2016) as a result of a longer stride length.

Foot strike patterns have been investigated as a potential kinematic factor that may influence RE because of differences in the length of the moment arm to the ankle plantarflexors created by forefoot and rearfoot strike patterns (Williams and Cavanagh, 1987). Theoretically, a forefoot strike pattern should allow an isometric state of contraction to be achieved throughout stance and elastic strain energy to be stored and released optimally (Fletcher and Macintosh, 2017). However, in the main, experimental evidence has failed to show differences in RE between forefoot, midfoot and rearfoot strikers across a range of running speeds (Cunningham et al., 2010; Gruber et al., 2013; Perl et al., 2012). It is likely that habituation to a footstrike pattern and differences in the running speed used to analyse kinematics confounds results of these studies. Heel strike patterns are often associated with an excessive displacement of the foot in front of the centre of mass at ground contact, which substantially increases braking forces (Lieberman et al., 2015). Although some gait re-training studies have demonstrated reductions in horizontal placement of the foot relative to centre of mass and decreased peak braking and propulsive forces, no effect on RE has been noted (Arendse et al., 2004; Fletcher et al., 2008; Heiderscheit et al., 2011).

Vertical oscillation of a runners centre of mass and reduced knee and hip range of motion during stance phase also appears to be related to RE (Folland et al., 2017; Moore, 2016). A small vertical displacement of centre of mass would imply that the joints of the lower limb move through a smaller range (possess higher leg spring stiffness) and thus perform less work against gravity, which would produce less vertical impulse with muscles acting closer to isometric (Slawinski and Billat, 2004; Teunissen et al., 2007). Acute increases in a runners vertical oscillation has been shown to increase energy cost (Egbuonu et al., 1990; Tseh et al., 2008), and reducing vertical displacement of centre of mass can improve RE (Halvorsen et al., 2012). It would also seem plausible that improving a runner’s maximum strength and rate of force development (RFD) would minimise the displacement of lower limb joints at ground contact and thus reduce vertical oscillation during stance.

An initial foot strike at ground contact that falls in front of the centre of mass will cause a horizontal braking effect, which momentarily reduces horizontal velocity and increases RE as a greater subsequent concentric force is required to maintain running speed compared to a smaller horizontal impulse (Moore, 2016). Indeed, horizontal velocity of the pelvis was recently used as a marker of this braking effect and was shown to be correlated with RE (Folland et al., 2017). In conjunction with this observation, a greater angle of dorsiflexion and shank angle relative to vertical, was also been shown to be negatively related to RE (Folland et al., 2017). Higher horizontal velocity of the heel and greater plantarflexion velocity have also been shown to be associated with better RE (Williams and Cavanagh, 1987). Presumably therefore, striking the ground with active ankle plantarflexion and the shank positioned closer to vertical (under the centre of mass) is likely to reduce horizontal braking impulse, aid in creating leg stiffness and optimise RE.

A less extended leg position at toe-off has consistently been shown to relate to superior RE (Cavanagh et al., 1977; Moore et al., 2014a; Moore et al., 2012; Williams and Cavanagh, 1987). In a fully extended position, based upon the length-tension relationship, muscles are at a poor length to generate force, therefore can contribute little to propulsion. Lower limb extension towards end range of motion also requires work to be performed concentrically, which incurs a high energy cost. Indeed, Moore et al. (2012) showed that novice runners improved their RE following a ten week training programme, with the extent of improvement being related to the degree of knee extension at toe-off. It was speculated that this strategy maximises effective force production and minimises energy cost of running via either performing less unnecessary work or reducing the distance the leg is required to travel during the subsequent swing phase.

Despite limited research coverage, it is generally accepted that upper limb biomechanics play an integral role in optimising RE (Moore, 2016). Natural arm swing during running appears to contribute to reducing vertical oscillation, counteracts the vertical angular momentum created by the lower limbs and aids in controlling excessive rotations in the torso and pectoral girdle (Moore, 2016). A lower level of transverse plane shoulder angular displacement and shoulder angular velocity was found to relate to better RE in Collegiate cross-country runners (Anderson and Tseh, 1994), however there are currently no studies which have investigated the influence of altering natural arm swing with an intervention, and the impact this has on RE.

Studies have attempted to improve RE via gait re-training techniques (Clansey et al., 2014; Craighead et al., 2014; Fletcher et al., 2008; Messier and Cirillo, 1989) or reduce stride length in runners identified as ‘over-striders’ (Morgan et al., 1994), but have generally shown no alteration in RE, despite alterations in running biomechanics. It may be possible that a greater running volume was required to habituate runners to the new technique, or that incorrect biomechanical factors were targeted (Moore, 2016). It therefore appears that the best strategy to lower energy cost via these kinematic and spatiotemporal factors is to allow runners to self-optimise through acquiring greater running experience.

In general, there appears to be an inverse relationship between flexibility and RE (Craib et al., 1996; Gleim et al., 1990; Hunter et al., 2011; Jones, 2002; Trehearn and Buresh, 2009), suggesting that being less flexible is beneficial for RE. However, this has not been a consistent findings, with other studies showing higher levels of flexibility relate to better RE (Beaudoin and Blum, 2005; Godges et al., 1989; Godges et al., 1993; Nelson et al., 2001). It has been suggested that inflexibility in joints, may limit range of motion, thus reduce energy expenditure and facilitate storage and return of elastic energy during running (Gleim et al., 1990; Jones, 2002). It is possible though that an optimal level of flexibility may exist at various joints, however this optimum range may be quite low for many joints of the lower limb and trunk. Results therefore depend upon the inter-individual variability in the flexibility of participants, which joints are assessed, and the sex of participants, as females are typically more flexible (Trehearn and Buresh, 2009). A systematic review on this topic concluded that pre-session stretching may enhance RE, however chronic stretching has little effect on RE (Shrier, 2004).

2.3.3 Speed at Maximal Oxygen Uptake and Critical Speed

Although $\dot{V}O_{2max}$ and RE are highly useful physiological parameters, they are of limited practical use to runners because they fail to provide a meaningful expression of running speed that can be used to prescribe training and predict performance (Jones, 2006). s$\dot{V}O_{2max}$ provides a composite measure of $\dot{V}O_{2max}$ and RE based upon the RE-speed relationship extrapolated via a linear regression line to the $\dot{V}O_{2max}$ value. As shown in Figure 2.5, a runner with superior (lower) RE at a range of sub-maximal speeds who possesses a similar $\dot{V}O_{2max}$ to another runner, is likely to have a superior s$\dot{V}O_{2max}$. As $\dot{V}O_{2max}$ represents a ceiling of an individual's aerobic metabolic power, a poor value will also generate a weak s$\dot{V}O_{2max}$ score. The amalgamation of several physiological qualities into this single determinant appears to more accurately differentiate performance, particularly in well-trained runners (McLaughlin et al., 2010; Noakes et al., 1990; Saunders et al., 2004b; Stratton et al., 2009). It has been suggested that the optimal running speed to develop $\dot{V}O_{2max}$ is at s$\dot{V}O_{2max}$ (Billat and Koralsztein, 1996; Wenger and Bell, 1986), thus this value has a high level of practical relevance for runners and their coaches.

The critical speed model, which represents exercise tolerance at boundary between the heavy and severe intensity domains, potentially offers an alternative to measurement of s$\dot{V}O_{2max}$ that is currently uninvestigated in runners (Denadai and Greco, 2017a; 2017b). Two main parameters can be assessed using the critical speed model; critical speed itself, which is defined as the lower boundary of the severe intensity domain, which when maintained to exhaustion leads to attainment of $\dot{V}O_{2max}$, and the curvature constant of the speed-time hyperbola above critical speed, which is represented by the total distance that can be covered prior to exhaustion at a constant speed (Jones et al., 2010). Middle-distance running performance (800 m) is strongly related to critical speed models (r = 0.83-0.94) in trained runners (Bosquet et al., 2006), and may be more important than RE in well-trained runners (Denadai and Greco, 2017b).

2.3.4 Fractional Utilisation and Lactate Threshold

The proportion of $\dot{V}O_{2max}$ that a runner can access and maintain for long periods is referred to as 'fractional utilisation', and is an important factor capable of predicting performance (Costill et al., 1973; Maughan and Leiper, 1983). A runner's speed at a reference point on the lactate-speed curve, or BL for a given running speed, are also important predictors of distance running performance (Farrell et al., 1979; Fay et al., 1989; Yoshida et al., 1993). The LT is represented by the first rise in the BL value (~1 $mMol{\cdot}L^{-1}$) from baseline (Jones et al., 1999), which in well-trained distance runners can be sustained for 1-2 h. With increasing intensity thereafter, the lactate turnpoint (LTP) can be identified as the second inflection point on the curve where the rise is more sudden and sustained (Kilding and Jones, 2005), usually between 2-4 $mMol{\cdot}L^{-1}$ (Jones, 2006). This running speed will usually be equivalent to a trained runners 10 km race pace (Jones, 2006). A runners LT corresponds closely with the fractional utilisation of $\dot{V}O_{2max}$ that can be sustained for a given distance (Bassett and Howley, 2000), therefore an increase in LT also allows a greater proportion of aerobic power to be accessed.

Measurement of BL offers practitioners with a useful way to evaluate performance and monitor changes over time. Identification of a runners speed associated with LT and LTP (sLTP) plus equivalent HR values allows coaches to individualise training pace zones more precisely. In general, continuous recovery runs should be performed at a speed below LT, intensities between LT and LTP used for steady running, LTP pace used for 'tempo' efforts (20-40 min), s$\dot{V}O_{2max}$ for extensive interval training to improve $\dot{V}O_{2max}$, and speeds faster than s$\dot{V}O_{2max}$ used for intensive interval training designed to develop anaerobic capabilities (Jones, 2006b; Laursen and Jenkins, 2002; Midgley et al., 2007a; Midgley et al., 2006b). A shift to the right of the speed-lactate curve represents an improvement in performance, which is primarily underpinned by metabolic adaptations relating to an ability to buffer and clear metabolites from the blood (Jones and Carter, 2000).

2.3.5 Anaerobic Determinants

The contribution of anaerobic factors to distance running performance is well-established (Brandon, 1995; Green and Patla, 1992). In particular, anaerobic capacity and neuromuscular capabilities are thought to play a large role in discriminating performance in runners who are closely matched from an aerobic perspective (Bulbulian et al., 1986; Paavolainen et al., 1999c). An individual's s$\dot{V}O_{2max}$ perhaps provides the most event-specific representation of neuromuscular capabilities in distance runners, however measures of maximal running speed and anaerobic capacity are also potentially important (Noakes, 1988).

The middle-distance events rely heavily on the capacity of anaerobic energy processes and the ability to tolerate high levels of metabolic acidosis (Thompson, 2017). BL values of ~20 $mMol{\cdot}L^{-1}$ have been observed following 800 m running in males and females, indicating a substantial contribution from anaerobic glycolytic energy sources (Lacour et al., 1990a). For an 800 m runner, near-maximal velocities of running are reached during the first 200 m of the race (Reardon, 2013), which necessitates a high capacity of the neuromuscular and anaerobic system. It has also been hypothesised that middle-distance runners who possess a higher maximal running speed and greater anaerobic capacity are able to compensate for a lower aerobic capacity (Brandon, 1995). Indeed, a negative relationship between aerobic and anaerobic capacity in an elite group of nine middle-distance and six long-distance runners has previously been observed (Crielaard and Pirnay, 1981).

A number of studies have investigated the relationship between anaerobic- and neuromuscular-related variables and performance in middle- and long-distance running events. Houmard and colleagues (1991) observed that counter-movement jump (CMJ) and power recorded during a Margaria run-test were related to 5 km time in well-trained male runners. Hudgins and colleagues (2013) also showed significant relationships between a three-step jump test and 800 m ($r = -0.83$) and 3 km ($r = -0.72$) time in 11 middle-distance runners. A relationship was also present between the same measure and 5 km ($r = -0.71$) performance in a group of 12 long-distance runners (Hudgins et al., 2013). Recently, significant relationships between 800 m performance and 20 m sprint ($r = 0.72$), 200 m sprint ($r = 0.84$), CMJ ($r = -0.69$), and loaded squat velocity ($r = -0.58$) were observed in national and international male 800 m runners (personal best range: 1.43 – 1.58) (Bachero-Mena et al., 2017). Sprint performances (300 m and 100 m) were also capable of explaining 85% of the inter-individual variability in 800 m performance in a group of 11 male runners (Deason et al., 1991), and similarly, 50 m sprint time has shown be to correlated with 10 km performance ($r = 0.62$) in females (Tharp et al., 1997). In addition, Paavolainen and associates (1999c) showed that speed during a 5 km correlated with 20 m sprint time ($r = 0.68$) and sMART ($r = 0.63$). This finding was later corroborated by Nummela and co-workers (2006) who showed that sMART correlated with 5 km TT speed ($r = 0.77$) and $\dot{V}O_{2max}$ ($r = 0.77$). The authors also argued that neural input was an important determinant of 5 km speed as the average electromyography (EMG) activity from five lower limb muscles was also related ($r = 0.60$) (Nummela et al., 2006).

Correlation findings are useful in helping to explain how much variability in distance running performance can be explained by an anaerobic or neuromuscular factor, but this does not imply that anaerobic capabilities are responsible for superior distance running performances. It has been recognised that ST activities are capable of improving measures of maximal strength and explosive power in middle- and long-distance runners (Beattie et al., 2014; Berryman et al., 2017; Jung, 2003; Ronnestad and Mujika, 2014), and that these improvements likely underpin the positive changes seen in physiological parameters such as RE (Denadai et al., 2017). Several reviews have also been conducted aiming to summarise the literature that has investigated the effect of ST interventions on sprint performance (Bolger et al., 2015; de Villarreal et al., 2012; Seitz et al., 2014), however no recent systematic review has documented whether ST provides benefits to anaerobic running capabilities in middle- and long-distance runners specifically.

2.3.6 Oxygen Uptake Kinetics

The $\dot{V}O_2$ kinetic response refers to the rate with which $\dot{V}O_2$ rises at the onset of exercise, and along with the other determinants of performance described herein, has been suggested to be an important determinant of middle- and long-distance running performance (Jones and Burnley, 2009). At the onset of exercise, the demand for energy increases rapidly, which is primarily accommodated by breakdown of phosphocreatine and anaerobic glycolysis to resynthesise adenosine triphosphate. The resultant rise in intra-muscular metabolites stimulates an increased rate of oxidative phosphorylation, that continues to rise in an exponential fashion ('fast component') until the demand for energy is met (defined by a steady state $\dot{V}O_2$). Above moderate intensities of running, a $\dot{V}O_2$ 'slow component' will be observable, which is characterised by a continued rise in $\dot{V}O_2$ and delays attainment of a steady state. A more rapid $\dot{V}O_2$ kinetic response therefore enhances muscle metabolic stability, accompanied by a lower oxygen deficit, thereby offsetting fatigue.

$\dot{V}O_2$ kinetics appear to be a more sensitive measure than more traditional determinants of performance such as $\dot{V}O_{2max}$ and BL markers when investigating the physiological response to an intervention (Koppo et al., 2004; Norris and Petersen, 1998; Phillips et al., 1995). Well-trained runners typically possess faster $\dot{V}O_2$ kinetics compared to lesser trained runners (Caputo and Denadai, 2004; Kilding et al., 2007), and elite distance runners have similar 'time constants' to thoroughbred racehorses (Jones and Poole, 2009). Kilding and co-workers (2006) found that long-distance runners possessed superior $\dot{V}O_2$ kinetics compared to middle-distance runners of a similar competitive status. The authors also observed that inter-individual differences in $\dot{V}O_2$ kinetic response could be partly explained by the volume of running training that runners were undertaking, irrespective of event specialism (Kilding et al., 2006). High concentrations of phosphocreatine in the muscle, that delays oxidative phosphorylation processes, are typically found in athletes with high anaerobic capacity, such as middle-distance runners (Berger and Jones, 2007; Kilding et al., 2006). This may also be a mechanism by which the $\dot{V}O_2$ kinetic response is limited during early stages of exercise (Meyer, 1988).

Research investigating strategies to improve the $\dot{V}O_2$ kinetic response have largely focussed on endurance training and the influence of pre-performance 'priming' exercise (Jones and Burnley, 2009). Endurance training interventions have been shown to increase the fast component of the $\dot{V}O_2$ kinetic response and reduce the slow component (Carter et al., 2000), although it is uncertain what type of training optimises adaptation (Poole and Jones, 2012). Section 2.6.2 discusses the effect of priming exercise on the $\dot{V}O_2$ kinetic response to a subsequent exercise bout.

2.4 Limitations to Performance in Adolescent Middle- and Long-Distance Runners

Despite extensive research investigating the physiological factors that underpin distance running performance in adults, less is known about the determinants of success in specific populations, such as adolescents. In studies that have assessed the relationship between physiological parameters and performance in young runners, participants have typically been homogenous for age, but may differ markedly in their maturation status (Beunen and Malina, 1988) and level of training (Wilson et al., 1999). This is likely to influence the extent to which physiological parameters correlate with performance measures compared to groups of well-trained adult runners, who generally have similar characteristics with respect to these confounding variables. Moreover, the method used to partition groups of young participants for differences in body size for variables such as $\dot{V}O_{2max}$ and RE is also likely to influence findings (Eisenmann et al., 2001).

In general, the physiological determinants of performance for adolescents appears to be similar to those of adult runners. A number of investigations have confirmed that $\dot{V}O_{2max}$ is a significant predictor (r=0.5-0.9) of performance for 1500 m (Abe et al., 1998; Almarwaey et al., 2003), 3 km (Abe et al., 1998; Mahon et al., 1996; Unnithan et al., 1995), 5 km (Abe et al., 1998; Cunningham, 1990) and cross-country (Cole et al., 2006; Fernhall et al., 1996) in young (10-18 years) groups of runners. RE (or $\dot{V}O_2$ at ventilatory threshold or LT) also appears to be related to middle- (Almarwaey et al., 2003; Mayers and Gutin, 1979; Unnithan et al., 1995) and long-distance performance (Cole et al., 2006; Fernhall et al., 1996), although this is not always the case (Abe et al., 1998; Cunningham, 1990). The discrepancy in findings in these studies is likely due to the small inter-individual variability in RE despite differences in running performance compared to other studies. Additionally, s$\dot{V}O_{2max}$ (Abe et al., 1998; Almarwaey et al., 2003; Cole et al., 2006; Cunningham, 1990) and fractional utilisation (Mahon et al., 1996; Unnithan et al., 1995) have also been shown to significantly correlate with distance running performance in adolescents.

Evidence for anaerobic variables contributing to performance is far less convincing in young distance runners compared to adult runners. Almarwaey and colleagues (2003) reported no significant relationship between Wingate test power and both 800 m and 1500 m performance in adolescent boys and girls. Similarly, CMJ height, muscle power and isokinetic knee extension and flexion strength have all been shown to be unrelated to 5 km performance in adolescent (16-18 years) runners (Cole et al., 2006; Dellagrana et al., 2015). Conversely, Mahon and co-authors (1996) showed that 55 m sprint and CMJ were significant predictors of 3 km TT in preadolescent children. This finding may simply be a reflection of individuals possessing high or low levels of athletic ability across the range of tests utilised, or the higher level of specificity in the tests used compared to other studies (Almarwaey et al., 2003; Cole et al., 2006; Dellagrana et al., 2015). Collectively, it seems measures of anaerobic and neuromuscular capabilities contribute little to distance running performance in adolescents. However, it is currently unknown whether anaerobic and strength-related factors are able to predict inter-individual variability in RE in this age-group, which is known to be partly underpinned by these attributes.

2.5 Chronic Effects of Strength Training on the Physiological Determinants of Middle- and Long-Distance Running Performance: A Systematic Review (Study 1)

2.5.1 Aim

Section 2.3 described the important physiological parameters that constrain middle- and long-distance running performance. The efficacy of ST on these determinants of performance has received considerable attention in the literature, however to date, the results of these studies have not been fully synthesised in a review on the topic. Consequently the aim of this systematic review was to analyse the evidence surrounding the use of ST on distance running parameters that includes both aerobic and anaerobic qualities, in addition to body composition and performance-related outcomes. This work also provides a forensic, critical evaluation that, unlike previous work, highlights areas that future investigations should address to improve methodological rigor, such as ensuring valid measurement of physiological parameters and maximising control over potential confounding factors.

2.5.2 Method

2.5.2.1 Literature Search Strategy

The PRISMA statement (Moher et al., 2009) was used as a basis for the procedures described herein. Electronic database searches were carried out in Pubmed, SPORTDiscus and Web of Science using the following search terms and Boolean operators: ("strength training" OR "resistance training" OR "weight training" OR "weight lifting" OR "plyometric training" OR "concurrent training") AND ("distance running" OR "endurance running" OR "distance runners" OR "endurance runners" OR "middle distance runners") AND ("anaerobic" OR "sprint" OR "speed" OR "performance" OR "time" OR "economy" OR "energy cost" OR "lactate" OR "maximal oxygen uptake" OR "VO2max" OR "aerobic" OR "time trial"). Searches were limited to papers published in English and from 1st January 1980 to 6th October 2017.

2.5.2.2 Inclusion and Exclusion Criteria

For a study to be eligible, each of the following inclusion criteria were met:

- Participants were middle- (800 m – 3000 m) or long-distance runners (5000 m – ultra-distance). Studies using triathletes and duathletes were also included because often these participants possess similar physiology to distance runners and complete similar volumes of running training.
- A ST intervention was applied. This was defined as heavy (less than nine repetition maximum (RM) loads and/or 80% of 1RM) or isometric resistance training (HRT), moderate

load (9-15 RM and/or 60-80% 1RM) RT, ERT, reactive ST or PT. Sprint training (SpT) could be used in conjunction with one or more of the above ST methods, but not exclusively as the only intervention activity.

- The intervention period lasted four weeks or longer. This criteria was employed as neuromuscular adaptations have been observed in as little as 4 weeks in non-strength trained individuals (Baroni et al., 2013; Mayhew et al., 1995).
- A running only control group (CG) was used that adopted similar running training to the intervention group(s)
- Data on one or more of the following physiological parameters was reported: $\dot{V}O_{2max}$, RE, s$\dot{V}O_{2max}$, TT performance, TTE, BL response, anaerobic capacity, maximal speed, measures of body composition
- Published in full in a peer-reviewed journal

Studies were excluded if any of the following criteria applied:

- Participants were non-runners (eg students, untrained/less than six months running experience). Further restrictions were not placed upon experience/training status.
- The running training and/or ST intervention was poorly controlled and/or reported
- The intervention involved only SpT or was embedded as part of running training sessions
- Participants were reported to be in poor health or symptomatic
- Ergogenic aids were used as part of the intervention

Using the mean $\dot{V}O_{2max}$ values provided within each study, participants training status was considered as moderately-trained (male $\dot{V}O_{2max}$ ≤55 $mL \cdot kg^{-1} \cdot min^{-1}$), well-trained (male $\dot{V}O_{2max}$ 55-65 $mL \cdot kg^{-1} \cdot min^{-1}$) or highly-trained (male $\dot{V}O_{2max}$ ≥65 $mL \cdot kg^{-1} \cdot min^{-1}$) (Denadai et al., 2017; Jones, 2006a). For female participants, the $\dot{V}O_{2max}$ thresholds were set 10 $mL \cdot kg^{-1} \cdot min^{-1}$ lower (Jones, 2006a). In the absence of $\dot{V}O_{2max}$ values, training status was based upon the training or competitive level of the participants: moderately-trained = recreational or local club, well-trained = Collegiate or provincial, highly-trained = national or international.

2.5.2.3 Study Selection

Figure 2.7 provides a visual overview of the study selection process. Search results were imported into a published software for systematic reviews (Ouzzani et al., 2016) which allowed a blind screening process to be performed by two independent reviewers (author and Principal Supervisor). Any disagreements were resolved by consensus. The initial search yielded 454 publications. Following the removal of duplicates (*n*=190), publications were filtered by reading the title and abstract (inter-rater reliability (IRR): 95.3%, Cohens *k* = 0.86) leaving 19 review articles or commentaries, and 47 potentially relevant papers, which were given full consideration. Five additional records were identified as being potentially relevant via manual searches of previously published reviews on this topic and the individual study citations. These 52 studies were considered in detail for appropriateness, resulting in a further 26 papers (Barnes et al., 2013b; Bluett et al., 2015; Childs et al., 2011; Chtara et al., 2005; Clark et al., 2017; Esteve-Lanao et al., 2008; Glowacki et al., 2004; Guglielmo et al., 2009; Hamilton et al., 2006; Hasegawa et al., 2011; Hickson, 1980; Hickson et al., 1988; Kelly et al., 2008; Maćkała and Stodółka, 2014; Mikkola et al., 2011; Roschel et al., 2015; Sato and Mokha, 2009; Saunders et al., 2004c; Sedano et al., 2013; Spurrs et al., 2002; Stohanzl et al., 2017; Taipale et al., 2010; Taipale et al., 2014; Taipale et al., 2013; Tong et al., 2016; Vorup et al., 2016) being excluded (IRR: 94.2%, Cohens k = 0.88) for the following reasons: not published in full in a peer-reviewed journal (Childs et al., 2011; Hasegawa et al., 2011; Saunders et al., 2004c; Spurrs et al., 2002), absence of a running only CG (Barnes et al., 2013b; Guglielmo et al., 2009; Hamilton et al., 2006; Hickson, 1980; Hickson et al., 1988; Maćkała and Stodółka, 2014; Mikkola et al., 2011; Roschel et al., 2015; Sedano et al., 2013; Taipale et al., 2010; Taipale et al., 2014; Taipale et al., 2013), participants were non-runners (Bluett et al., 2015; Chtara et al., 2005; Glowacki et al., 2004; Kelly et al., 2008), no physiological parameters were measured (Esteve-Lanao et al., 2008), dissimilar running training was applied between groups (Vorup et al., 2016), the ST intervention was poorly controlled (Hamilton et al., 2006), and the intervention did not involve one of the aforementioned types of ST (Clark et al., 2017; Sato and Mokha, 2009; Stohanzl et al., 2017; Tong et al., 2016).

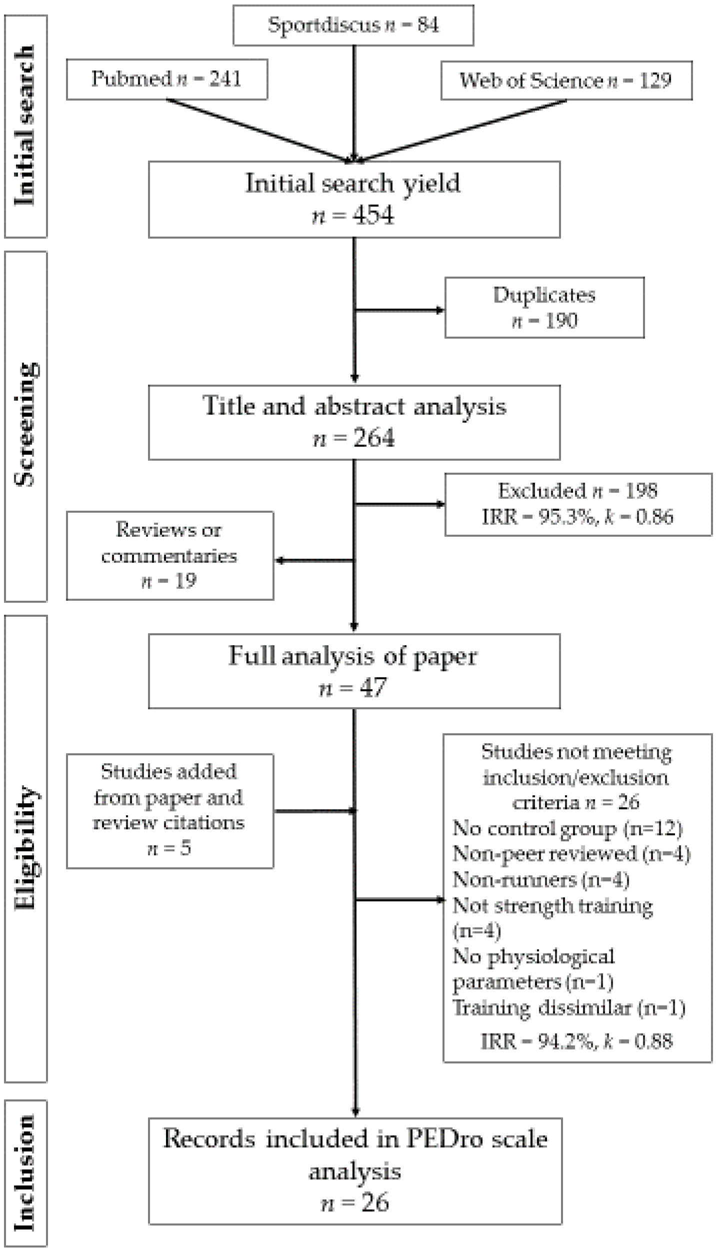


Figure 2.7. Search, screening and selection process for suitable studies. IRR = inter-rater reliability.

2.5.2.4 Analysis of Results

The Physiotherapy Evidence Database (PEDro) scale was subsequently used to assess the quality of the remaining 26 records (Albracht and Arampatzis, 2013; Beattie et al., 2017; Berryman et al., 2010; Bertuzzi et al., 2013; Bonacci et al., 2011; Damasceno et al., 2015; Ferrauti et al., 2010; Fletcher et al., 2010; Giovanelli et al., 2017; Johnston et al., 1997; Karsten et al., 2016; Mikkola et al., 2007; Millet et al., 2002; Paavolainen et al., 1999a; Pellegrino et al., 2016; Piacentini et al., 2013; Ramirez-Campillo et al., 2014; Saunders et al., 2006; Schumann et al., 2015; Schumann et al., 2016; Skovgaard et al., 2014; Spurrs et al., 2003; Storen et al., 2008; Turner et al., 2003; Vikmoen et al., 2016; Vikmoen et al., 2017) by the two independent reviewers. Two studies reported their results across two papers (Schumann et al., 2015; Schumann et al., 2016; Vikmoen et al., 2016; Vikmoen et al., 2017), therefore both are considered as single studies hereafter, thus a total of 24 studies were analysed. The PEDro scale is a tool recommended for assessing the quality of evidence when systematically reviewing randomised-controlled trials (Maher et al., 2003). Each paper is scrutinised against eleven items relating to the scientific rigor of the methodology, with items 2-11 being scored 0 or 1. Papers are therefore awarded a rating from 0 to 10 depending upon the number of items which the study methodology satisfies (10 = study possesses excellent internal validity, 0 = study has poor internal validity). No studies were not excluded based upon their PEDro scale score and IRR was excellent (93.2%, Cohens k = 0.86).

Results are summarised as a percentage change and the p-value for variables relating to: strength outcomes, RE, $\dot{V}O_{2max}$, s$\dot{V}O_{2max}$, BL response, TT, anaerobic performance and body composition. Due to the heterogeneity of outcome measures in the included studies and the limitations associated with conditional probability, where possible, an effect size (ES) statistic (Cohens d) is also provided. ES values are based upon those reported in the studies or were calculated using the ratio between the change score (post-intervention value minus pre-intervention value) and a pooled standard deviation (SD) at baseline for intervention and CGs. Values were interpreted as trivial <0.20; small 0.20-0.59; moderate 0.60-1.20; and large >1.20.

2.5.3 Results

2.5.3.1 Participant Characteristics

A summary of the participant characteristics for the 24 studies which met the criteria for inclusion in this review is presented in Table 2.1. A total of 469 participants (male n=352, female n=96) are included, aged between 17.3 – 44.8 years. $\dot{V}O_{2max}$ data were reported for all but five studies (Albracht and Arampatzis, 2013; Bonacci et al., 2011; Piacentini et al., 2013; Ramirez-Campillo et al., 2014; Schumann et al., 2015; Schumann et al., 2016) and ranged from 47.0 to 70.4 $mL \cdot kg^{-1} \cdot min^{-1}$. Based upon weighted mean values in the studies that reported participant characteristics for each group, age (30.2 vs 29.0 years), body mass (68.1 vs 70.0 kg), height (1.74 vs 1.74 m) and $\dot{V}O_{2max}$ (57.3 vs 57.7 $mL \cdot kg^{-1} \cdot min^{-1}$) appeared to differ little at baseline for ST groups and CGs respectively. Moderately trained or recreational level runners were used in nine studies (Albracht and Arampatzis, 2013; Bonacci et al., 2011; Ferrauti et al., 2010; Johnston et al., 1997; Karsten et al., 2016; Pellegrino et al., 2016; Piacentini et al., 2013; Schumann et al., 2015; Schumann et al., 2016; Turner et al., 2003), well-trained participants in ten studies (Beattie et al., 2017; Berryman et al., 2010; Bertuzzi et al., 2013; Damasceno et al., 2015; Giovanelli et al., 2017; Paavolainen et al., 1999a; Skovgaard et al., 2014; Spurrs et al., 2003; Storen et al., 2008; Vikmoen et al., 2016; Vikmoen et al., 2017), and highly-trained or national/international runners were used in four studies (Fletcher et al., 2010; Millet et al., 2002; Ramirez-Campillo et al., 2014; Saunders et al., 2006). National caliber junior runners were also used in one investigation (Mikkola et al., 2007). Participants took part or competed in events ranging from the middle-distances to ultra-marathons, and several studies used triathletes (Bonacci et al., 2011; Karsten et al., 2016; Millet et al., 2002) or duathletes (Vikmoen et al., 2016; Vikmoen et al., 2017).

2.5.3.2 Study Design and PEDro Scores

Table 2.1 also provides an overview of several important features of study design, including PEDro scale scores. Studies lasted 6-14 weeks with the exception of two investigations, which lasted 24 weeks (Schumann et al., 2015; Schumann et al., 2016) and 40 weeks (Beattie et al., 2017). Fourteen studies provided detailed accounts of the running training undertaken by the participants. However these were usually reported from monitoring records, thus only three studies were deemed to have appropriately controlled for the volume and intensity of running in both groups (Berryman et al., 2010; Paavolainen et al., 1999a; Schumann et al., 2015; Schumann et al., 2016; Vikmoen et al., 2016; Vikmoen et al., 2017). Six studies provided little or no detail on the running training that participants performed (Albracht and Arampatzis, 2013; Beattie et al., 2017; Fletcher et al., 2010; Karsten et al., 2016; Pellegrino et al., 2016; Piacentini et al., 2013). ST in all but three investigations (Mikkola et al., 2007; Paavolainen et al., 1999a; Skovgaard et al., 2014) was supplementary to running training, and one paper provided the CG with alternative activities (stretching and core stability) matched for training time (Saunders et al., 2006).

Studies all scored a 4, 5 or 6 on the PEDro scale. All investigations had points deducted for items relating to blinding of participants, therapists and assessors. Differences in the scores awarded were mainly the result of studies not randomly allocating participants to groups and failing to obtain data for more than 85% of participants initially allocated to groups; or this information not being explicitly stated.

2.5.3.3 Training Programmes

Table 2.2 provides a summary of the training characteristics associated with the ST intervention and running training used concurrently as part of the study period. The ST activities used were RT or HRT (Albracht and Arampatzis, 2013; Bertuzzi et al., 2013; Damasceno et al., 2015; Ferrauti et al., 2010; Fletcher et al., 2010; Johnston et al., 1997; Karsten et al., 2016; Mikkola et al., 2007; Piacentini et al., 2013; Storen et al., 2008; Vikmoen et al., 2016; Vikmoen et al., 2017), PT (Berryman et al., 2010; Pellegrino et al., 2016; Ramirez-Campillo et al., 2014; Spurrs et al., 2003; Turner et al., 2003), ERT (Berryman et al., 2010), or a combination of these methods (Beattie et al., 2017; Bonacci et al., 2011; Giovanelli et al., 2017; Saunders et al., 2006; Schumann et al., 2015; Schumann et al., 2016), which in some cases also included SpT (Millet et al., 2002; Paavolainen et al., 1999a; Skovgaard et al., 2014).

All studies utilised at least one multi-joint, closed kinetic chain exercise with the exception of two studies that used isometric contractions on the ankle plantarflexors (Albracht and Arampatzis, 2013; Fletcher et al., 2010). One study employed only resistance machine exercises for lower limb HRT (Ferrauti et al., 2010), whereas all other studies used free weights, bodyweight resistance or a combination of machines and free weights. ST (using lower limb musculature) was scheduled once (Beattie et al., 2017; Berryman et al., 2010; Ferrauti et al., 2010), twice (Beattie et al., 2017; Bertuzzi et al., 2013; Damasceno et al., 2015; Karsten et al., 2016; Mikkola et al., 2007; Piacentini et al., 2013; Ramirez-Campillo et al., 2014; Schumann et al., 2015; Schumann et al., 2016; Spurrs et al., 2003; Vikmoen et al., 2016; Vikmoen et al., 2017), three times (Bonacci et al., 2011; Fletcher et al., 2010; Giovanelli et al., 2017; Johnston et al., 1997; Millet et al., 2002; Saunders et al., 2006; Skovgaard et al., 2014; Spurrs et al., 2003; Storen et al., 2008; Turner et al., 2003), or four times (Albracht and Arampatzis, 2013) per week. One study used 15 sessions over a six week period (Pellegrino et al., 2016) and one study reported 2.7 h of ST activity per week (Paavolainen et al., 1999a).

HRT was typically prescribed in 2-6 sets of 3-10 repetitions per exercise at relatively heavy loads (higher than 70% 1RM or to repetition failure). PT prescription consisted of 1-6 exercises performed over 1-6 sets of 4-10 repetitions, totalling 30-228 foot contacts per session. Most studies applied the principle of progressive overload and some authors reported periodised models for the intervention period (Beattie et al., 2017; Damasceno et al., 2015; Giovanelli et al., 2017; Saunders et al., 2006; Skovgaard et al., 2014; Vikmoen et al., 2016; Vikmoen et al., 2017). Studies which included SpT tended to utilise short distances (20-150 m), over 4-12 sets at maximal intensity (Millet et al., 2002; Paavolainen et al., 1999a; Skovgaard et al., 2014). ST was supervised or part-supervised across all studies with the exception of three, one which was unsupervised (Turner et al., 2003) and two where it was unclear from the report (Millet et al., 2002; Paavolainen et al., 1999a).

Running training varied considerably (16-170 $km \cdot wk^{-1}$, 3-9 $sessions \cdot wk^{-1}$) across the studies, with various levels of detail provided regarding weekly volume and intensity. Importantly, all studies that added ST reported that running training did not differ between groups.

2.5.3.4 Strength Outcomes

All but two studies (Bonacci et al., 2011; Karsten et al., 2016) measured at least one strength-related parameter (Table 2.3). Across all studies that used 1RM testing (Beattie et al., 2017; Bertuzzi et al., 2013; Damasceno et al., 2015; Johnston et al., 1997; Mikkola et al., 2007; Millet et al., 2002; Piacentini et al., 2013; Schumann et al., 2015; Schumann et al., 2016; Skovgaard et al., 2014; Storen et al., 2008), the intervention produced a statistically significant improvement (4-33%, ES: 0.7-2.4). Maximal voluntary contraction (MVC) was also used to assess strength capacity in seven papers, with the majority reporting improved (7-34%, ES: 0.38-1.65) scores following ST (Albracht and Arampatzis, 2013; Ferrauti et al., 2010; Mikkola et al., 2007; Paavolainen et al., 1999a; Spurrs et al., 2003) but others reporting no difference compared to a CG (Ferrauti et al., 2010; Fletcher et al., 2010; Schumann et al., 2015; Schumann et al., 2016). Performance on a jump test was shown to improve (3-9%, ES: 0.25-0.65) in some studies (Berryman et al., 2010; Millet et al., 2002; Paavolainen et al., 1999a; Ramirez-Campillo et al., 2014; Vikmoen et al., 2016), however other studies showed no change compared to a CG (Beattie et al., 2017; Mikkola et al., 2007; Pellegrino et al., 2016; Saunders et al., 2006; Schumann et al., 2015; Schumann et al., 2016; Turner et al., 2003) and in one study the CG improved to a greater extent than the intervention group (Piacentini et al., 2013). Changes in an ability to produce force rapidly also showed mixed results, with some studies showing improvements in peak power output (Berryman et al., 2010) and RFD (Mikkola et al., 2007; Storen et al., 2008) and others showing no change in these parameters (Giovanelli et al., 2017; Saunders et al., 2006; Spurrs et al., 2003). Similarly, stiffness, when measured directly or indirectly (using reactive strength index) during non-running tasks, has been shown to improve (ES: 0.43-0.90) (Albracht and Arampatzis, 2013; Piacentini et al., 2013; Ramirez-Campillo et al., 2014; Spurrs et al., 2003) and remain unchanged (Beattie et al., 2017; Damasceno et al., 2015; Millet et al., 2002) following ST. Vertical or leg stiffness during running showed improvements (10%, ES: 0.33) at relatively slow speeds (Giovanelli et al., 2017) and also at 3 km race pace (ES: 1.2) following ST (Millet et al., 2002).

2.5.3.5 Running Economy

An assessment of RE was included in all but four (Bertuzzi et al., 2013; Karsten et al., 2016; Ramirez-Campillo et al., 2014; Schumann et al., 2015; Schumann et al., 2016) of the studies in this review (Table 2.3). RE was quantified as the oxygen cost of running at a given speed in every case, except in three studies where a calculation of energy cost was used (Albracht and Arampatzis, 2013; Fletcher et al., 2010; Pellegrino et al., 2016). Statistically significant improvements (2-8%, ES: 0.14-3.22) in RE were observed for at least one speed in 14 papers. A single measure of RE was reported in four of these papers (Berryman et al., 2010; Karsten et al., 2016; Skovgaard et al., 2014; Storen et al., 2008), and a further four studies assessed RE across multiple different speeds and found improvements across all measures taken (Albracht and Arampatzis, 2013; Johnston et al., 1997; Millet et al., 2002; Spurrs et al., 2003). Six papers reported a mixture of significant and non-significant results from the intensities they used to evaluate RE (Giovanelli et al., 2017; Mikkola et al., 2007; Paavolainen et al., 1999a; Piacentini et al., 2013; Saunders et al., 2006; Turner et al., 2003). Six studies failed to show any significant improvements in RE compared to a CG (Bonacci et al., 2011; Damasceno et al., 2015; Ferrauti et al., 2010; Fletcher et al., 2010; Pellegrino et al., 2016; Vikmoen et al., 2016).

2.5.3.6 Maximal Oxygen Uptake

No statistically significant changes were reported in $\dot{V}O_{2max}$ or peak oxygen uptake during a maximal test ($\dot{V}O_{2peak}$) for any group in the majority of studies that assessed this parameter (Berryman et al., 2010; Bertuzzi et al., 2013; Damasceno et al., 2015; Giovanelli et al., 2017; Johnston et al., 1997; Karsten et al., 2016; Mikkola et al., 2007; Millet et al., 2002; Saunders et al., 2006; Skovgaard et al., 2014; Spurrs et al., 2003; Storen et al., 2008; Vikmoen et al., 2016). Three papers observed improvements for $\dot{V}O_{2max}$ in the intervention group, but the change in score did not differ significantly from that of the CG (Beattie et al., 2017; Ferrauti et al., 2010; Pellegrino et al., 2016). One study detected a significant improvement (4.9%) in $\dot{V}O_{2max}$ for the CG compared to the intervention group (Paavolainen et al., 1999a).

2.5.3.7 Speed Associated with $\dot{V}O_{2max}$

Nine studies provided data on s$\dot{V}O_{2max}$ or a similar metric (Beattie et al., 2017; Berryman et al., 2010; Bertuzzi et al., 2013; Damasceno et al., 2015; Giovanelli et al., 2017; Karsten et al., 2016; Mikkola et al., 2007; Millet et al., 2002; Vikmoen et al., 2016). Just two of these papers reported statistically significant improvements (3-4%, ES: 0.42-0.49) in the ST group compared to the CG (Berryman et al., 2010; Damasceno et al., 2015). One study (Millet et al., 2002) reported a 2.6% improvement (ES: 0.57) and another (Beattie et al., 2017) a 4.0% increase (ES: 0.9) after a 40 week intervention, however these changes were not significantly different to the CG.

2.5.3.8 Blood Lactate Parameters

BL value was measured at fixed velocities in six studies (Albracht and Arampatzis, 2013; Ferrauti et al., 2010; Fletcher et al., 2010; Mikkola et al., 2007; Saunders et al., 2006; Schumann et al., 2016) and speed assessed for fixed concentrations of BL (2-4 $mMol \cdot L^{-1}$) or LT in six studies (Beattie et al., 2017; Ferrauti et al., 2010; Pellegrino et al., 2016; Schumann et al., 2015; Storen et al., 2008; Vikmoen et al., 2016). One study using young participants observed significantly greater improvements (11-12%) at two speeds compared to the CG (Mikkola et al., 2007). Other studies found no significant changes following the intervention (Albracht and Arampatzis, 2013; Beattie et al., 2017; Fletcher et al., 2010; Pellegrino et al., 2016; Saunders et al., 2006; Storen et al., 2008; Vikmoen et al., 2016) or a change which was not superior to the CG (Ferrauti et al., 2010; Schumann et al., 2015; Schumann et al., 2016).

2.5.3.9 Time Trial Performance

To assess the impact of ST directly upon distance running performance, studies utilised a TT over 1000 m (preceded by 5x1 km) (Schumann et al., 2015; Schumann et al., 2016), 1500 m (Skovgaard et al., 2014), 2.4 km (Ramirez-Campillo et al., 2014), 3 km (Berryman et al., 2010; Pellegrino et al., 2016; Spurrs et al., 2003), 5 km (Karsten et al., 2016; Paavolainen et al., 1999a), 10 km (Damasceno et al., 2015; Skovgaard et al., 2014), 5 min (Vikmoen et al., 2016), and 40 min (Vikmoen et al., 2017). There were similarities to competitive scenarios in most studies, including performances taking place under race conditions (Karsten et al., 2016; Pellegrino et al., 2016; Ramirez-Campillo et al., 2014; Schumann et al., 2015; Schumann et al., 2016; Spurrs et al., 2003), on an outdoor athletics track (Damasceno et al., 2015; Karsten et al., 2016; Ramirez-Campillo et al., 2014; Skovgaard et al., 2014), on an indoor athletics track (Berryman et al., 2010; Paavolainen et al., 1999a; Pellegrino et al., 2016; Schumann et al., 2015; Schumann et al., 2016; Spurrs et al., 2003), and following a prolonged (90 min) submaximal run (Vikmoen et al., 2017). Performance improvements were statistically significant compared to a CG for eight of the 12 trials. The exceptions were a 40 min TT (Vikmoen et al., 2017), a 1000 m repetition (Schumann et al., 2015; Schumann et al., 2016), and two studies that used a 3 km TT (Berryman et al., 2010; Spurrs et al., 2003). Statistically significant 3 km improvements were observed for all groups in one case (Berryman et al., 2010), however the ES was larger for the two intervention groups (0.37 and 0.46) compared to the CG (0.20). Improvements over middle-distances (1500 m – 3000 m) were generally moderate (3-5%, ES: 0.4-1.0). Moderate to large effects (ES: >1.0) were observed for two studies (Karsten et al., 2016; Skovgaard et al., 2014) that evaluated performance over longer distances (5 – 10 km), however the relative improvements were quite similar (2-4%) over long distances compared to shorter distances (Damasceno et al., 2015; Karsten et al., 2016; Paavolainen et al., 1999a; Skovgaard et al., 2014).

2.5.3.10 Anaerobic Outcomes

Tests relating to anaerobic determinants of distance running performance were used in five investigations. Sprint speed over 20 m (Paavolainen et al., 1999a; Ramirez-Campillo et al., 2014) and 30 m (Mikkola et al., 2007) showed statistically significant improvements following ST (1.1-3.4%). Two studies provided evidence for enhancement of sMART (Mikkola et al., 2007; Paavolainen et al., 1999a), and one further study showed no change in anaerobic running distance after six weeks of HRT (Karsten et al., 2016). A 30 s Wingate test was also used in one paper, however no differences in performance were noted (Damasceno et al., 2015).

2.5.3.11 Body Composition

Body mass did not change from baseline in 18 of the studies (Albracht and Arampatzis, 2013; Beattie et al., 2017; Berryman et al., 2010; Bonacci et al., 2011; Damasceno et al., 2015; Ferrauti et al., 2010; Giovanelli et al., 2017; Johnston et al., 1997; Millet et al., 2002; Paavolainen et al., 1999a; Piacentini et al., 2013; Ramirez-Campillo et al., 2014; Saunders et al., 2006; Skovgaard et al., 2014; Spurrs et al., 2003; Storen et al., 2008; Vikmoen et al., 2016; Vikmoen et al., 2017), however one investigation reported a significant increase (2%, ES: 0.32) following ST (Mikkola et al., 2007). This study also documented changes in the thickness of quadriceps femoris muscle in both the intervention (3.9%, ES: 0.35) and CG (1.9%, ES: 0.10) (Mikkola et al., 2007). Similarly, an increase in total lean mass (3%) and leg lean mass (3%) was found following 12 weeks of ST despite little alteration in cross-sectional area of the vastus lateralis and body mass being noted (Schumann et al., 2015; Schumann et al., 2016). Another study observed a significant decrease (-1.2%) in body mass in the CG, with no change in the intervention group (Vikmoen et al., 2016). A significant increase in leg mass (3.1%, ES: 1.69) was also noted in this study (Vikmoen et al., 2016; Vikmoen et al., 2017). Other indices of body composition that exhibited no significant changes were: fat mass (Beattie et al., 2017; Giovanelli et al., 2017; Johnston et al., 1997; Mikkola et al., 2007; Paavolainen et al., 1999a; Piacentini et al., 2013), fat-free mass (Giovanelli et al., 2017; Johnston et al., 1997; Piacentini et al., 2013), lean muscle mass (Beattie et al., 2017; Mikkola et al., 2007), skinfolds (Bonacci et al., 2011; Damasceno et al., 2015), and limb girth measurements (Bonacci et al., 2011; Johnston et al., 1997; Paavolainen et al., 1999a).

Table 2.1. Participant characteristics and design of each study.

C = control group, CS = core stability, F = female, h = hours, HRT = heavy resistance training, I = intervention group, M = male, PT = plyometric training, RT = resistance training, RT_{WBV} = resistance training with whole body vibration, $\dot{V}O_{2max}$ = maximal oxygen uptake, wk = week.

Study	Participant characteristics					Study Design				
	n (I/C)	Sex	Age (years)	$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	Training background (event specialism)	Duration (weeks)	Randomised?	Running controlled?	ST added or replace running?	PEDro score
Albracht & Arampatzis	26 (13/13)	M	I=27, C=25	-	Recreational (≥ 3 runs.wk^{-1}, 30-120 km.wk^{-1})	14	No	No	Added	5
Beattie et al.	20 (11/9)	M=19 F=1	I=29.5, C=27.4	I=59.6, C=63.2	Collegiate and national level (1500 m-10 km)	40	No	No	Added	4
Berryman et al.	28 (HRT *n*=12, PT *n*=11, C *n*=5)	M	HRT=31, PT=29, C=29	HRT=57.5, PT=57.5, C=55.7	3-7 runs.wk^{-1}. Provincial level (5 km – marathon)	8	Yes	Yes	Added	5
Bertuzzi et al.	22 (RT_{WBV} *n*=8, RT *n*=8, C *n*=6)	M	RT_{WBV}=34, RT=31, C=33	RT_{WBV}=56.3, RT=57.4, C=56.1	Local 10 km (35-45 min) race competitors	6	Yes	No (monitored)	Added	6
Bonacci et al.	8 (3/5)	M=5 F=3	21.6	-	Moderately-trained triathletes (34.8 km.wk^{1})	8	Yes	No (monitored)	Added	5
Damasceno et al.	18 (9/9)	M	I=34.1, C=32.9	I=54.3, C=55.8	Local 10 km (35-45 min) race competitors	8	Yes	No (monitored)	Added	6
Ferrauti et al.	20 (11/9)	M=14 F=6	40.0	I=52.0, C=51.1	Experienced (8.7 years) recreational (4.6 h.wk^{-1})	8	Yes	No (monitored)	Added	6

Fletcher et al.	1 2 (6/6)	M	I=22.2, C=26.3	I=67.3, C=67.6	Regional/national/ international level (1500 m – marathon)	8	Yes	No	Added	6
Giovanelli et al.	25 (13/12)	M	I=36.3, C=40.3	I=55.2, C=55.6	Experienced (11.7 years, >60 km.wk^{-1}) ultra-distance competitors	12	Yes	No (monitored)	Added	6
Johnston et al.	12 (6/6)	F	30.3	I=50.5, C=51.5	>1 year experience, 20-30 miles.wk^{-1}, 4-5 days.wk^{-1}	10	Yes	No (monitored)	Added	6
Karsten et al.	16 (8/8)	M=11 F=5	I=39, C=30	I=47.3, C=47.0	Recreational triathletes (>2 years, 3-5 days.wk^{-1}, 180-300 min.wk^{-1})	6	Yes	No	Added	6
Mikkola et al.	25 (13/12)	M=18 F=7	I=17.3, C=17.3	I=62.4, C=61.8	High-school runners (>2 years)	8	No	No (monitored)	Replace (I: 19%, C: 4%)	4
Millet et al.	15 (7/8)	M	I=24.3, C=21.4	I=69.7, C=67.6	Experienced (6.8 years) triathletes (*n*=7 national/international)	14	Yes	No (monitored)	Added	6
Paavolainen et al.	18 (10/8)	M	I=23, C=24	I=63.7, C=65.1	Experienced (8 years) cross-country runners (545 h.year^{-1})	9	Unclear (matched on $\dot{V}O_{2max}$ & 5 km)	Yes	Replace (I: 32%, C: 3%)	4
Pellegrino et al.	22 (11/11)	M=14 F=8	I=34.2, C=32.5	I=48.0, C=47.7	Experienced recreational (local clubs and races)	6	Yes	No	Added	6
Piacentini et al.	16 (HRT *n*=6, RT *n*=5, C *n*=5)	M=16 F=4	HRT=44. 2	-	Local (>5 years, 4-5 days.wk^{-1}) masters	6	Yes	No	Added	4

Table 2.1 (continued)

			RT=44.8 C=43.2		runners (10 km – marathon)					
Ramírez-Campillo et al.	32 (17/15)	M=19 F=13	22.1	-	National/international competitive level (1500 m – marathon)	6	Yes	No (monitored)	Added	6
Saunders et al.	15 (7/8)	M	I=23.4, C=24.9	I=67.7, C=70.4	National/international competitive level (3 km)	9	Yes	No (monitored)	Added (but C matched with stretching/ CS)	6
Schumann et al.	27 (13/14)	M	33	-	Recreational (>12 months; ≥ 2 runs.wk^{-1})	24	Unclear (matched by performance)	Yes	Added	5
Skovgaard et al.	21 (12/9)	M	31.1	59.4	Experienced (7.5 years) recreational (29.7 km.wk^{-1}, 3.3 runs.wk^{-1})	8	Yes	Yes (I only)	Replace (I: 42%)	6
Spurrs et al.	17 (8/9)	M	25	I=57.6, C=57.8	Experienced (10 years); 60-80 km.wk^{-1}	6	Yes	No (monitored)	Added	6
Støren et al.	17 (8/9)	M=9 F=8	I=28.6, C=29.7	I=61.4, C=56.5	Well-trained (5 km: M=18.42, F=19.23)	8	Yes	No (monitored)	Added	6
Turner et al.	18 (10/8)	M=8 F=10	I=31, C=27	I=50.4, C=54.0	Basic training (>6 months; ≥ 3 runs.wk^{-1})	6	Yes	No (monitored)	Added	6
Vikmoen et al.	19 (11/8)	F	I=31.5, C=34.9	53.3	Well-trained (duathletes)	11	Yes	Yes	Added	5

Table 2.1 (continued)

Table 2.2. Intervention and running training variables.

AIT = aerobic interval training, BW = body weight, CMJ = counter-movement jump, C = control group, CS = core stability, DJ = drop jump, ERT = explosive resistance training, ET = endurance training (eg cycling, swimming, roller skiing), GCT = ground contact time, h = hours, HIIT = high-intensity interval training, HR_{max} = maximum heart rate (predicted from 220-age), HRT = heavy resistance training, I = intervention group, LB = lower body, LSD = long slow distance run, MVC = maximum voluntary contraction, PPO = peak power output, PT = plyometric training, RDL = Romanian deadlift, RM = repetition maximum, RT = resistance training, SpT = sprint training, ST = strength training, UB = upper body, RT_{WBV} = resistance training with whole body vibration

Study	Intervention type	Main exercises	Frequency	Volume per session	Intensity	ST supervised?	Recovery between sessions	Running training
Albracht & Arampatzis	HRT (isometric)	Ankle plantarflexion (5° dorsiflexion, knee extended, 40° hip flexion)	4 per week	4 sets x 4 reps (3 s loading, 3 s relaxation)	90% MVC (adjusted weekly)	Yes	-	I: 66 $km.wk^{-1}$ C: 62 $km.wk^{-1}$
Beattie et al.	HRT/ERT/ PT	PT: pogo jumps, depth jumps, CMJ HRT: back squat, RDL, lunge ERT: jump squats	Wk 1-20: 2 per week; Wk 21-40: 1 per week	9-12 sets (2-3 sets per exercise); PT: 4-5 reps, HRT: 3-8 reps, ERT: 3 reps	Load progressed when competent	Yes	≥ 48 h between sessions (wk 1-20). Separate session to running	Not reported (usual running training)
Berryman et al.	ERT and PT	ERT: concentric squats PT: DJ	1 per week	ERT and PT: 3-6 sets x 8 reps	ERT: >95% PPO PT: 20-60 cm so rebound >95% CMJ	Yes	-	2 x AIT (1x peak speed, 1x80% peak speed) 1 x LSD (30-60 min)
Bertuzzi et al.	RT and RT_{WBV}	Half-squats	2 per week	3-6 sets x 4-10 reps periodised	70-100% 1RM over 12 weeks	Yes	Different days to runs	57-61 $km.wk^{-1}$

Bonacci et al.	PT/ERT	PT: CMJ, knee lifts, ankle jumps, bounds, skips, hurdle jumps ERT: Squat jumps, back ext., hamstring curls	3 per week	PT: 1-5 sets x 5-10 reps or 20-30 m RT: 2-5 sets x 8-15 reps	Max height / fast velocity	Yes	-	Same as previous 3 months. I: swim (7.3 km), cycle (137.6 km), run (34.8 km) C: swim (10.1 km), cycle (147.5 km), run (29.0 km)
Damasceno et al.	HRT	Half-squat, leg press, calf raise, knee ext.	2 per week	2-3 sets x 3-10 reps	10RM periodised to 3RM	Yes	72 h between HRT sessions. Different days to runs	36-41 km.wk^{-1} @50-70% $\dot{V}O_{2max}$
Ferrauti et al.	HRT	Machines: leg press, knee ext., knee flexion, hip ext., ankle ext.; UB exercises	1 per week LB; 1 per week UB	LB: 4 sets x 3-5 reps	3-5 RM	Yes	-	I: 240 min.wk^{-1}, C: 276 min.wk^{-1}
Fletcher et al.	HRT (isometric)	Plantarflexions	3 per week	4 sets x 20 s	80% MVC	Yes	-	70-170 km.wk^{-1}
Giovanelli et al.	CS/RT (4wk) HRT/ERT/PT (8wk)	CS: 6 exercises (eg planks) RT/HRT: single leg half-squat, step-up, lunges ERT: CMJ, split squat PT: jump rope, high knees	3 per week	5-8 exercises, 1-3 sets x 6-15 reps (30 s rest)	-	Partly (only wk 1 and 2)	≥ 48 h between sessions. Not day after races/AIT	I: normal running training C: 70-140 km.wk^{-1}, 5-7 sessions.wk^{-1}

Table 2.2 (continued)

Johnston et al.	HRT	Squats, lunge, heel raises (straight- and bent-leg), knee ext./flexion, 8xUB exercises	3 per week	3 sets x 6 reps squat and lunge; 2 sets x 20/12 reps bent-/straight-leg heel raise; 3 sets x 8 reps knee ext./flexion	RM each set	Yes	≥ 48 h between HRT sessions. ≥ 5 h between HRT and running sessions.	4-5 $days.wk^{-1}$, 32-48 $km.wk^{-1}$
Karsten et al.	HRT	RDL, squat, calf raises, lunges	2 per week	4 sets x 4 reps	80% 1RM	Yes	≥ 48 h between HRT sessions.	3-5 sessions/ 180-300 $min.wk^{-1}$
Mikkola et al.	SpT/PT/ERT	PT: alternative, calf, squat, hurdle jumps ERT: Squat, calf raise, hurdle jump, leg ext./curl	3 per week (each intervention type once)	SpT: 5-10 sets x 30-150 m PT/ERT: 2-3 sets x 6-10 reps	PT: BW ERT: low load, high velocity	Unclear	-	I: 8.8 $h.wk^{-1}$, C: 8.5 $h.wk^{-1}$
Millet et al.	HRT	Hamstring curl, leg press, seated press, squat, leg ext., heel raise	3 per week	3-5 sets x 3-5 reps	>90% 1RM (reassessed every 3 weeks)	Yes	Separate session to running	Total: I=7 $h.wk^{-1}$, C=6.6 $h.wk^{-1}$; Running: I=48 $km.wk^{-1}$, C=44 $km.wk^{-1}$
Paavolainen et al.	SpT/PT/ERT	PT: alternative, drop and hurdle jumps, CMJ, hops ERT: leg press, knee ext. and flexion	Not reported; 2.7 h per week	SpT: 5-10 sets x 20-100 m PT/ERT: 5-20 $reps.set^{-1}$ / 30-200 $reps.session^{-1}$	PT: BW or barbell ERT: 0-40% 1RM	Unclear	-	I: 8.4 $h.wk^{-1}$ (9 sessions) C: 9.2 $h.wk^{-1}$ (8 sessions)

Table 2.2 (continued)

Pellegrino et al.	PT	Modified version of Spurrs et al. (jumps, bounds, hops)	15 sessions total	60-228 foot contacts	Progressively increased	Yes	-	I: 34.4-36.2 $km.wk^{-1}$ C: 29.5-31.3 $km.wk^{-1}$
Piacentini et al.	HRT and RT	Squat, calf press, lunges, eccentric quad, calf raise, leg press + UB exercises	2 per week	HRT: 4 sets x 3-4 reps RT: 3 sets x 10 reps	HRT: 85-90% 1RM RT: 70% 1RM	Yes	-	4-5 $days.wk^{-1}$, 50 $km.wk^{-1}$
Ramírez-Campillo et al.	PT	DJ	2 per week	60 contacts (6 sets x 10 reps)	20 reps @20 cm, 20 reps @40 cm, 20 reps @60 cm	Yes	≥ 48 h between PT sessions. Performed before runs.	I: 64.7 $km.wk^{-1}$ C: 70.0 $km.wk^{-1}$ (AIT preferred)
Saunders et al.	PT/HRT	PT: CMJ, ankle jumps, bounds, skips, hurdle jumps, scissor jumps HRT: back ext., leg press, hamstring curls	3 per week	PT: Progress from 1-6 sets x 6-10 reps/10-30 m HRT: 1-5 sets x 6-10 reps (except back ext.)	PT: fast GCT HRT: Leg press 60% 1RM	Yes	-	107 $km.wk^{-1}$ (3x AIT, 1x LSD 60-150 min, 3x LSD 30-60 min, 3-6x LSD 20-40 min)
Schumann et al.	HRT/ERT/PT	HRT: leg press, knee flexion, calf raise +UB/core exercises ERT: Squat jumps, step-ups PT: Drop jumps, hurdle jumps	2 per week	HRT (wks 5-24): 5-12 reps per set	HRT (wks 5-24): 60-85% 1RM ERT: 20-30% 1RM	Yes	Same session as running. >48 h between sessions	Weekly: 2x run (35-45 min/65-85% HRmax), 2x LSD (35-40 min & 70-125 min/60-65% HRmax), 1-2x AIT and HIIT

Table 2.2 (continued)

Skovgaard et al.	SpT/HRT	HRT: squat, deadlift, leg press	SpT x 2 per week HRT x 1 per week	SpT: 4-12 sets x 30 s (3 min rest) HRT: 3-4 sets x 6-8 reps wks 1-4; 4 sets x 4 reps wks 5-8	SpT: maximal effort HRT: 15RM to 8RM wks 1-4; 4RM wks 5-8	Yes	3-4 d between SpT/HRT sessions. Different days to runs	I: AIT (4x4+2min @85% HR_{max}); 50 min @75-85% HR_{max} C: 40 km total (4 km AIT)
Spurrs et al.	PT	Jumps, bounds, hops	2-3 per week	60-180 foot contacts	Bilateral progressed to unilateral and greater height	Yes	Separate session to running	60-80 km per week
Støren et al.	HRT	Half-squats	3 per week	4 sets x 4 reps	4RM	Yes	-	I: 253 $min.wk^{-1}$ (+119 min other ET) C: 154 $min.wk^{-1}$ (+120 min other ET)
Turner et al.	PT	Vertical jumps and hops (continuous and intermittent), split jumps, uphill jumps	3 per week	40-110 foot contacts (5-30 s per exercise)	Bodyweight, short contact time	No (logbooks)	Performed in running sessions	Continued regular running (≥ 3 $runs.wk^{-1}$, ≥ 10 $miles.wk^{-1}$)
Vikmoen et al.	HRT	Machines: Half-squats, unilateral leg press, cable hip flexion, calf raises	2 per week	3 sets x 4-10 reps (periodised 3wk cycles)	Sets performed to RM failure	Partly (1 session per weeks 3-11)	HRT first session or performed on different days	4.3 $sessions.wk^{-1}$; 3.7 h @60-82% HR_{max}, 1.1 h @83-87% HR_{max}, 0.8 h @>87% HR_{max}

Table 2.2 (continued)

Table 2.3. Outcomes of the studies. Percentage changes, effect size (ES) and *p*-value only reported for statistically significant group results or ES > 0.2. All results presented are for the intervention (I) group unless stated (eg C = control). Variables measured where no-significance (NS) difference for time (pre- vs post-score) and no group x time (GxT) interaction was detected, are also listed.

ARD = anaerobic running distance, BJ = broad jump, BL = blood lactate, CMJ = counter-movement jump, C = control group, DJ = drop jump, DJ_{RSI} = drop jump reactive strength index, EC = energy cost, EMG = electromyography, ERT = explosive resistance training, FFM = fat-free mass, FU = fractional utilization, GCT = ground contact time, GRF = ground reaction force, HR = heart rate, HRT = heavy resistance training, I = intervention group, k_{leg} = leg stiffness, k_{vert} = vertical stiffness, (s)LT = (speed at) lactate threshold, MAS = maximal aerobic speed, MTS = musculotendinous stiffness, MVC = maximum voluntary contraction, PPO = peak power output, PT = plyometric training, QF = quadriceps femoris, RCP = respiratory compensation point (V_E/VCO_2), RFD = rate of force development, RM = repetition maximum, RMR = resting metabolic rate, RT = resistance training, RT_{WBV} = resistance training with whole body vibration, SJ = squat jump, TT = time trial, TTE = time to exhaustion, s = speed, sMART = speed during maximal anaerobic running test, $\dot{V}O_2$ = oxygen uptake, $\dot{V}O_{2max}$ / $\dot{V}O_{2peak}$ = highest oxygen uptake associated with a maximal aerobic exercise test, s$\dot{V}O_{2max}$ = speed associated with $\dot{V}O_{2max}$, Wk = week

Study	Main strength outcomes	Economy	$\dot{V}O_{2max}$ / $\dot{V}O_{2peak}$	s$\dot{V}O_{2max}$	Blood Lactate	Time trial	Anaerobic measures	Body composition
Albracht & Arampatzis	Plantarflexion MVC (6.7%, ES=0.56, p=0.004), max Achilles tendon force (7.0%, ES=0.55, p<0.01), Tendon stiffness (15.8%, ES=0.90, p<0.001)	$\dot{V}O_2$@10.8 km.h^{-1} (5.0%, ES=0.79) @12.6 km.h^{-1} (3.4%, ES=0.51). EC@10.8 km.h^{-1} (4.6%, ES=0.61) @12.6 km.h^{-1} (3.5%, ES=0.50), all p<0.05	-	-	BL@10.8 and 12.6 km.h^{-1}, NS	-	-	Body mass, NS
Beattie et al.	1RM back squat (wk 0-20: 19.3%, ES=1.2, p=0.001) DJ_{RSI} (wk 0-20: 7.3%, ES=0.3, NS GxT; wk	Ave. of 5 speeds Wk 0-20: 5.0%, ES=1.0, p=0.01.	Wk 0-20: 0.1%, ES=0.1, p=0.013.	Wk 0-20: 3.5%, ES=0.7, NS.	s2mMol.L^{-1}, s4mMol.L^{-1}, NS	-	-	Body mass, fat and lean muscle, NS

	0-40: 14.6%, ES=0.5, NS GxT) CMJ (wk 0-20: 11.5%, ES=0.5, NS GxT; wk 0-40: 11.5%, ES=0.6, NS GxT)	Wk 0-40: 3.5%, ES=0.6, NS.	Wk 0-40, I: 7.4%, ES=0.5, p=0.003, C: 2.8%, ES=0.6, NS	Wk 0-40: 4.0%, ES=0.9, NS				
Berryman et al.	PPO (ERT: 15.4%, ES=0.98, p<0.01; PT: 3.4%, ES=0.24, p<0.01). CMJ (ERT: 4.5%, ES=0.25, p<0.01; PT: 6.0%, ES=0.52, p<0.01)	@12 km.h^{-1} ERT: 4%, ES=0.62, p<0.01. PT: 7%, ES=1.01, p<0.01	NS	ERT: 4.2%, ES=0.43, p<0.01. PT: 4.2%, ES=0.49, p<0.01	-	3 km TT ERT: 4.1%, ES=0.37. PT: 4.8%, ES=0.46. C: 3.0%, ES=0.20; all p<0.05, GxT NS	-	Body mass, NS
Bertuzzi et al.	1RM half squat (RT: 17%, p≤0.05; RT$_{WBV}$: 18%, p≤0.05)	-	NS	NS	-	-	-	-
Bonacci et al.	-	@12 km.h^{-1} (after 45 min AIT cycle) NS	-		-	-	-	Body mass, skinfolds, thigh and calf girth, NS
Damasceno et al.	1RM half-squat (23%, ES=1.41, p<0.05), DJ$_{RSI}$, wingate test NS	@12 km.h^{-1} NS	NS	$s\dot{V}O_{2max}$ (2.9%, ES=0.42, p<0.05)	-	10 km TT (2.5%, p=0.039), increased speed in final 7 laps (p<0.05)	30 s Wingate test, NS	Body mass and skinfold, NS

Table 2.3 (continued)

Ferrauti et al.	Leg extension MVC (33.9%, ES=1.65, p<0.001); leg flexion MVC (9.4%, ES=0.38, NS)	@LT (ES=0.40, p<0.05, NS GxT) @8.6 and 10.1 km.h^{-1}, NS FU@10.1 km.h^{-1} (ES=0.61, p=0.05 GxT)	5.6%, ES=0.40, NS GxT	-	BL@10.1 km.h^{-1} (I: 13.1%, C: 12.1%, NS GxT). s4 mMol.L^{-1} (I: 4.2%, C: 2.6%, NS GxT).	-	-	Body mass, NS
Fletcher et al.	Isometric MVC (I: 21.6%, C: 13.4%), NS GxT	EC@75,85,95% sLT, NS	-	-	BL@ 75,85,95% sLT, NS.	-	-	-
Giovanelli et al.	SJ PPO, NS k_{leg}@10 km.h^{-1}, (9.5%, ES=0.33, p=0.034), @12 km.h^{-1} (10.1%, ES=0.33, p=0.038). k_{vert} @8,10,12,14 km.h^{-1}, NS	@8 km.h^{-1} (6.5%, ES=0.43, p=0.005), @10 km.h^{-1} (3.5%, ES=0.48, p=0.032), @12 km.h^{-1} (4.0%, ES=0.34, p=0.020), @14 km.h^{-1} (3.2%, ES=0.35, p=0.022), @RCP NS	NS	NS	-	-	-	Body mass, FFM, fat mass, NS
Johnston et al.	1RM squat (40%, p<0.05), knee flexion (27%, p<0.05)	@12.8 km.h^{-1} (4.1%, ES=1.76, p<0.05), @13.8 km.h^{-1} (3.8%, ES=1.61, p<0.05)	NS	-	-	-	-	Body mass, fat mass, FFM, limb girth, NS
Karsten et al.	-	-	NS	NS	-	5 km TT (3.5%, ES=1.06, p=0.002)	ARD, NS	-

Table 2.3 (continued)

Mikkola et al.	MVC (8%), 1RM (4%), RFD (31%) on leg press; all p<0.05. CMJ and 5-bounds, NS	@14 $km.h^{-1}$ (2.7%, ES=0.32, p<0.05), @10,12,13 $km.h^{-1}$, NS	NS	NS	BL@12 $km.h^{-1}$ (12%, p<0.05), @14 $km.h^{-1}$ (11%, p<0.05)	-	sMART (3.0%, p<0.01), s30 m sprint (1.1%, p<0.01)	Body mass (2%, ES=0.32, p<0.01). Thickness of QF (I: 3.9%, ES=0.35, p<0.01; C: 1.9%, ES=0.10, p<0.05); fat%, lean mass, NS
Millet et al.	1RM half-squat (25%, p<0.01), 1RM heel raise (17%, p<0.01), hop height (3.3%, p<0.05) k_{leg}@3km pace (ES=1.2, p<0.05) GCT, hop stiffness, NS	@75% v$\dot{V}O_{2max}$ (7.4%, ES=1.14, p<0.05) @~92% $\dot{V}O_{2max}$ (5.9%, ES=1.15, p<0.05)	NS	2.6%, ES=0.57, p<0.01, NS GxT	-	-	-	Body mass, NS
Paavolainen et al.	MVC knee extension (7.1%, p<0.01), 5BJ (4.6%, p<0.01)	@15 $km.h^{-1}$ (8.1%, ES=3.22, p<0.001) @13.2 $km.h^{-1}$, NS $\dot{V}O_2$ @LT, NS	C: (4.9%, p<0.05) $\dot{V}O_{2max}$ demand (3.7%, p<0.05, NS GxT)	-	-	5 km TT (3.1%, p<0.05)	s20 m (3.4%, ES=0.77, p<0.01) sMART (ES=1.98, p<0.001)	Body mass, fat %, calf and thigh girth, NS
Pellegrino et al.	CMJ (5.2%, p=0.045, NS GxT)	@10.6 $km.h^{-1}$ (1.3%, p<0.05 group) NS GxT @7.7, 9.2, 12.1, 13.5, 15.0, 16.4 $km.h^{-1}$, NS.	5.2%, ES=0.49, p=0.03, NS GxT	-	sLT, NS	3km TT (2.6%, ES=0.20, p=0.04)	-	-

Table 2.3 (continued)

Piacentini et al.	1RM leg press (HRT: 17%, ES=0.69, p<0.05), CMJ (C: 7%, ES=0.63, p<0.05), SJ (C: 13%, ES=0.83, p<0.01), Stiffness (RT: 13%, ES=0.64, p<0.05)	@10.75 $km.h^{-1}$ /marathon pace (HRT: 6.2%, p<0.05). @9.75,11.75 $km.h^{-1}$, NS	-	-	-	-	-	Body mass, fat mass, FFM, RMR, NS
Ramírez-Campillo et al.	CMJ (8.9%, ES=0.51, p<0.01), DJ @20 cm (12.7%, ES=0.43, p<0.01), DJ @40 cm (16.7%, ES=0.6, p<0.05)	-	-	-	-	2.4 km TT (3.9%, ES=0.4, p<0.05)	20 m sprint (2.3%, ES=0.3, p<0.01)	Body mass, NS
Saunders et al.	SJ RFD and peak force, NS. 5CMJ, NS	@18 $km.h^{-1}$ (4.1%, ES=0.35, p<0.05) @14,16 $km.h^{-1}$, NS	NS	-	BL @14,16,18 $km.h^{-1}$, NS	-	-	Body mass, NS
Schumann et al.	1RM leg press (I: NS, C: -4.7%, p=0.011), MVC leg flexion (-9.7%, p=0.031, ES=0.96, NS GxT), MVC leg press NS, MVC knee ext. NS, CMJ NS	-	-	-	BL during 6x1 km (I: NS, C:, 21%, NS GxT) s4 $mMol.L^{-1}$ (I: 6%, C: 8%, NS GxT).	1 km TT after 5x 1 km, 60 s rec. (I: 9%, C: 13%, NS GxT)	-	Body mass, NS; CSA vastus lateralis (group diff. I: 7%, C: -6%, NS GxT); Total and leg lean mass (I: 2%, NS GxT)
Skovgaard et al.	1RM squat (wk 4: 3.8%, wk 8: 12%, p<0.001); 1RM leg press (wk 4: 8%, p<0.05; wk 8: 18%,	@12 $km.h^{-1}$ (wk 8: 3.1%, ES=1.53, p<0.01)	NS	-	-	10 km TT (wk 4: 3.8%, ES=1.50, p<0.05).	-	Body mass, NS

Table 2.3 (continued)

	$p<0.001$), 5RM deadlift (wk 4: 14%, wk8: 22%, $p<0.001$)					1500 m TT (wk 8: 5.5%, ES=0.67, $p<0.001$)		
Spurrs et al.	MTS @75% MVC (left: 14.9%, right: 10.9%, $p<0.05$), Calf MVC (left: 11.4%, right: 13.6%, $p<0.05$). RFD NS	@12 km.h^{-1} (6.7%, ES=0.45), 14 km.h^{-1} (6.4%, ES=0.45), 16 km.h^{-1} (4.1%, ES=0.30), all $p<0.01$	NS	-	-	3km TT (2.7%, ES=0.13, $p<0.05$, NS GxT)	-	Body mass, NS
Støren et al.	1RM (33.2%, $p<0.01$) and RFD (26%, $p<0.01$) half-squat	@70% $\dot{V}O_{2max}$ (5%, ES=1.03, $p<0.01$)	NS	-	sLT, LT %$\dot{V}O_{2max}$, NS	-	-	Body mass, NS
Turner et al.	CMJ and SJ, NS	Ave. of 3 speeds: M=9.6, 11.3, 12.9, F=8.0, 9.6, 11.3 km.h^{-1} (2-3%, $p\leq0.05$) @9.6 km.h^{-1}, NS	-	-	-	-	-	-
Vikmoen et al.	1RM half-squat (45%, ES=2.4, $p<0.01$), SJ (8.9%, ES=0.83, $p<0.05$), CMJ (5.9%, ES=0.65, $p<0.05$)	@10 km.h^{-1}, NS	NS	NS	s3.5 mMol.L^{-1}, NS	5 min TT (4.7%, ES=0.95, $p<0.05$). 40 min TT, NS		I: Leg mass (3.1%, ES=1.69, $p<0.05$), body mass, NS C: Leg mass (-2.2%), body mass decrease (-1.2%, $p<0.05$)

Table 2.3 (continued)

2.5.4 Discussion

The aim of this systematic review was to identify and evaluate current literature which investigated the effects of ST exercise on the physiological determinants of middle- and long-distance running performance. The addition of new research published in this area, and the application of more liberal criteria provided results for 50% more participants (*n*=469) compared to a recent review on RE (Denadai et al., 2017). Based upon the data presented herein, it appears that ST activities can positively affect performance directly and provide benefits to several physiological parameters that are important for distance running. However, inconsistencies exist within the literature, that can be attributed to differences in methodologies and characteristics of study participants, thus practitioners should be cautious when applying generalised recommendations to their athletes. Despite the moderate PEDro scores (4, 5, or 6), the quality of the works reviewed in this paper are generally considered acceptable when the unavoidable constraints imposed by a training intervention study (related to blinding) are taken into account.

2.5.4.1 Running Economy

RE is influenced by a variety of factors, including force-related and stretch-shortening cycle qualities, which can be improved with ST activities. In general, a ST intervention, lasting 6-20 weeks, added to the training programme of a distance runner appears to enhance RE by 2-8%. This finding is in agreement with previous meta-analytical reviews in this area that show concurrent training has a beneficial effect (~4%) on RE (Balsalobre-Fernandez et al., 2016; Denadai et al., 2017). In real terms, an improvement in RE of this magnitude should theoretically allow a runner to operate at a lower relative intensity and thus improve training and/or race performance. No studies attempted to demonstrate this link directly, although inferences were made in studies, which noted improvements in RE and performance separately (Berryman et al., 2010; Paavolainen et al., 1999a; Skovgaard et al., 2014). Other works provide evidence that small alterations in RE (~1.1%) directly translate to changes (~0.8%) in sub-maximal (Hoogkamer et al., 2016) and maximal running performance (Frederick et al., 1984). The typical error (TE) of measurement of RE has been reported to be 1-2% (Morgan et al., 1991; Pereira and Freedson, 1997; Saunders et al., 2004b) and the smallest worthwhile change (SWC) ~2% (Hoogkamer et al., 2016; Saunders et al., 2004b; Shaw et al., 2013), which is thought to represent a ‘real’ improvement and not simply a change due to variability of the measure. Taken together, it is therefore likely that the improvements seen in RE following a period of concurrent training would represent a meaningful change in performance.

Improvements were observed in moderately-trained (Albracht and Arampatzis, 2013; Johnston et al., 1997; Piacentini et al., 2013; Turner et al., 2003), well-trained (Beattie et al., 2017; Berryman et al., 2010; Giovanelli et al., 2017; Paavolainen et al., 1999a; Skovgaard et al., 2014; Spurrs et al., 2003; Storen et al., 2008) and highly-trained participants (Millet et al., 2002; Saunders et al., 2006), suggesting runners of any training status can benefit from ST. Different modes of ST were utilised in the studies, with RT or HRT (Albracht and Arampatzis, 2013; Johnston et al., 1997; Mikkola et al., 2007; Piacentini et al., 2013; Storen et al., 2008), ERT (Berryman et al., 2010), PT (Berryman et al., 2010; Spurrs et al., 2003; Turner et al., 2003), and a combination of these activities (Beattie et al., 2017; Giovanelli et al., 2017; Saunders et al., 2006), all augmenting RE to a similar extent. Single-joint isometric RT may also provide a benefit if performed at a high frequency (4 $d \cdot wk^{-1}$) (Albracht and Arampatzis, 2013). Several studies adopted a periodised approach to the types of ST prioritised during each 3-6 week cycle (Beattie et al., 2017; Giovanelli et al., 2017; Saunders et al., 2006; Skovgaard et al., 2014), which is likely to provide the best strategy to optimise gains long-term (Rhea and Alderman, 2004).

Six studies (Bonacci et al., 2011; Damasceno et al., 2015; Ferrauti et al., 2010; Fletcher et al., 2010; Pellegrino et al., 2016; Vikmoen et al., 2016) failed to show any improvement in RE and a further six (Giovanelli et al., 2017; Mikkola et al., 2007; Paavolainen et al., 1999a; Piacentini et al., 2013; Saunders et al., 2006; Turner et al., 2003) observed both improvements and an absence of change at various speeds. This implies benefits are more likely to occur under specific conditions relating to the choice of exercises, participant characteristics, and speed used to measure RE. In most studies that observed a benefit, exercises with free weights were utilised (Beattie et al., 2017; Giovanelli et al., 2017; Johnston et al., 1997; Millet et al., 2002; Piacentini et al., 2013; Skovgaard et al., 2014). Multi-joint exercises using free weights are likely to provide a superior neuromuscular stimulus compared to machine-based or single-joint exercises as they demand greater levels of co-ordination, multi-planar control, activation of synergistic muscle groups (McCaw and Friday, 1994; Schwanbeck et al., 2009) and usually require force to be produced from closed-kinetic chain positions. These types of exercise also have a greater biomechanical similarity to the running action so are therefore likely to provide a greater level of specificity and hence transfer of training effect (Young, 2006). An insufficient overload or a lack of movement pattern specificity may therefore be the reason for the absence of an effect in studies that used only resistance machines (Ferrauti et al., 2010; Vikmoen et al., 2016) or a single-joint exercise (Fletcher et al., 2010). These studies were also characterised by a lower frequency of sessions compared to studies that used similar RT exercises but did observe an improvement in RE (Albracht and Arampatzis, 2013; Mikkola et al., 2007).

Moderately-trained runners were used in three of the six studies showing an absence of effect (Bonacci et al., 2011; Ferrauti et al., 2010; Pellegrino et al., 2016) and one used triathletes who performed a relatively low volume of running (34.8 $km \cdot wk^{-1}$) as part of their training (Bonacci et al., 2011). However, a similar number of studies used recreational athletes did show a positive effect (Albracht and Arampatzis, 2013; Johnston et al., 1997; Piacentini et al., 2013; Turner et al., 2003), suggesting that training level is unlikely to be the reason for the lack of response in these studies. This is also confirmed by recent observations that showed improvement in RE following a period of concurrent training was similar across individuals irrespective of training status and the number of sessions per week ST was performed (Denadai et al., 2017).

The speed used to assess RE may also explain the discrepancies in results across studies. It has been suggested that runners are most economical at the speeds they practice at most (Saunders et al., 2004b), and for investigations that utilised PT, stretch-shortening cycle improvements are likely to manifest at high running speeds where elastic mechanisms have greatest contribution (Bonacci et al., 2011; Cavagna and Kaneko, 1977). Therefore a velocity-specific measurement of RE may be the most valid strategy to establish whether an improvement has occurred. For example, Saunders and associates (2006) observed an improvement (p=0.02, ES: 0.35) at 18 $km{\cdot}h^{-1}$ in elite runners, but an absence of change at slower speeds. Similarly, Millet and colleagues (2002) noted large (ES: > 1.1) improvements at speeds faster than 75% s$\dot{V}O_{2max}$ (~15 $km{\cdot}h^{-1}$) in highly-trained triathletes, and Paavolainen et al. (1999a) detected changes at 15 $km{\cdot}h^{-1}$ but not slower speeds in well-trained runners. Furthermore, Piacentini and co-workers (2013) found improvement at race-pace in recreational marathon runners but not at a slower and a faster speed. Improvements observed at faster compared to slower speeds may also reflect improvements in motor unit recruitment as a consequence of ST. As running speed increases there is a requirement for greater peak vertical forces due to shorter ground contact times, that elevates metabolic cost (Fletcher and MacIntosh, 2017). To produce higher forces, yet overcome a reduction in force per motor unit as a consequence of a faster shortening velocity, more motor unit recruitment is required (Barnes and Kilding, 2015a). Thus, an increase in absolute motor unit recruitment following a period of ST would result in a lower relative intensity reducing the necessity to recruit higher threshold motor units during running (Fletcher and MacIntosh, 2017). Several studies that failed to show any response used a single speed to assess RE (Bonacci et al., 2011; Damasceno et al., 2015; Vikmoen et al., 2016), perhaps indicating that the speed selected was unsuitable to capture an improvement. Furthermore, only a small number of studies used relative speeds (Beattie et al., 2017; Ferrauti et al., 2010; Fletcher et al., 2010; Millet et al., 2002; Storen et al., 2008), with most choosing to assess participants at the same absolute intensity. A given speed for one runner may represent a high relative intensity, whereas for another runner it may be a relatively low intensity. Therefore selecting the same absolute speed in a group heterogeneous with respect to $\dot{V}O_{2max}$, may not provide a true reflection of any changes which take place following an intervention. Moreover, this may also confound any potential improvements observed in fractional utilisation of $\dot{V}O_{2max}$.

Several common procedural issues exist in the studies reviewed, which may influence the interpretation of results and therefore conclusions drawn. The majority of studies quantified RE and $\dot{V}O_{2max}$ as a ratio to body mass, however $\dot{V}O_2$ does not show a linear relationship with increasing body size (Bergh et al., 1991). It is also known that the relationship between body size and metabolic response varies across intensities, with a trend for an increasing size exponent as individuals move from low-intensity towards maximal exercise (Batterham and Jackson, 2003; Markovic et al., 2007).

Moreover, allometric scaling is likely to decrease inter-individual variability (Helgerud, 1994), potentially improving the validity of observations . Ratio-scaling RE for all velocities to body mass is therefore theoretically and statistically inappropriate (Curran-Everett, 2013). Just two studies (Berryman et al., 2010; Storen et al., 2008) used an appropriate allometric scaling exponent (0.75) to account for the non-linearity associated with $\dot{V}O_2$ response to differences in body mass, both establishing a large ES in their results. The unsuitability of ratio-scaling as a normalisation technique when processing physiological data is likely to have influenced the statistical outcomes of some studies and thus inaccurate conclusions may have been generated.

RE was expressed as oxygen cost in all but three studies (Albracht and Arampatzis, 2013; Fletcher et al., 2010; Pellegrino et al., 2016), which quantified RE using the energy cost method. As the energy yield from the oxidation of carbohydrates and lipids differs, subtle alterations in substrate utilisation during exercise can confound measurement of RE when expressed simply as an oxygen uptake ($\dot{V}O_2$) value. Energy cost is therefore the more valid metric for expressing economy, compared to traditional oxygen cost, as metabolic energy expenditure can be calculated using the respiratory exchange ratio, thus accounting for differences in substrate utilisation (Fletcher et al., 2009; Shaw et al., 2014). Despite attempts to control for confounding variables such as diet and lifestyle in most studies, equivalence in inter-trial substrate utilization cannot be guaranteed, which may have impacted upon the measurement of RE.

2.5.4.2 Maximal Oxygen Uptake

Thirteen works in this review found no change in $\dot{V}O_{2max}$ following the intervention period, demonstrating that although ST does not appear to positively influence $\dot{V}O_{2max}$, it also does not hinder aerobic power. Although ST in most studies was supplementary to running training, it appears that the additional physiological stimulus provided by ST was insufficient to elicit changes in cardiovascular-related parameters (Hurley et al., 1984). Three studies did observe significant increases in aerobic power that did not differ to the change observed in the CG (Beattie et al., 2017; Ferrauti et al., 2010; Pellegrino et al., 2016), and one further study found an improvement in $\dot{V}O_{2max}$ in the CG only (Mikkola et al., 2007). It is perhaps surprising that more studies did not find an increase in $\dot{V}O_{2max}$ (in any group) given that participants continued their normal running training through the study period. Improvements in $\dot{V}O_{2max}$ of 5-10% have been shown following relatively short periods (<6 weeks) of endurance training (Jones and Carter, 2000), however the magnitude of changes is dependent upon a variety of factors including the initial fitness level of individuals and the duration and nature of the training programme (Wenger and Bell, 1986). $\dot{V}O_{2max}$ is known to have an innate upper limit for each individual, therefore in highly-trained and elite runners, long-term performance improvement is likely to result from enhancement of other physiological determinants, such as RE, fractional utilisation and s$\dot{V}O_{2max}$ (Billat and Koralsztein, 1996; Martin et al., 1986;

Morgan et al., 1989). A number of studies used moderately-trained participants (Beattie et al., 2014; Ferrauti et al., 2010; Johnston et al., 1997; Pellegrino et al., 2016; Turner et al., 2003), who would be the most likely to show an improvement in $\dot{V}O_{2max}$ following a 6-14 week period of running, with two investigations demonstrating improvements for both groups (Ferrauti et al., 2010; Pellegrino et al., 2016). The absence of $\dot{V}O_{2max}$ improvement in other papers suggests that the duration of the study and/or the training stimulus, was insufficient to generate an improvement (Wenger and Bell, 1986). Indeed, one study of 40 weeks duration in Collegiate level runners observed similar improvements (ES: 0.5-0.6) in $\dot{V}O_{2max}$ in both groups (Beattie et al., 2017), suggesting a longer time period may be required to detect changes in runners with a higher training status. High-intensity aerobic training (>80% $\dot{V}O_{2max}$) is a potent stimulus for driving changes in $\dot{V}O_{2max}$ (Midgley et al., 2006b), however some studies reported runners predominantly utilised low-intensity (<70% $\dot{V}O_{2max}$) continuous running (Damasceno et al., 2015; Mikkola et al., 2007; Millet et al., 2002), which may also explain the lack of changes observed.

2.5.4.3 Speed Associated with $\dot{V}O_{2max}$

Improvements for s$\dot{V}O_{2max}$ (3-4%, ES: 0.42-0.49) were found in two investigations (Berryman et al., 2010; Damasceno et al., 2015), with a further two studies observing improvements (2.6-4.0%, ES: 0.57-0.9) that could not be ascribed to the training differences between the groups (Beattie et al., 2017; Millet et al., 2002). A number of studies also found little change in s$\dot{V}O_{2max}$ following an intervention (Bertuzzi et al., 2013; Giovanelli et al., 2017; Karsten et al., 2016; Mikkola et al., 2007; Vikmoen et al., 2016). As s$\dot{V}O_{2max}$ is the product of the interaction between aerobic and neuromuscular variables, a small improvement in one area of physiology may not necessarily result in an increase in s$\dot{V}O_{2max}$. Damasceno et al. (2015) found an improvement in s$\dot{V}O_{2max}$ (2.9%, $p<0.05$, ES: 0.42) despite detecting no change in $\dot{V}O_{2max}$, RE or Wingate performance, therefore attributed the change to the large improvements (23%, ES: 1.41) in the force producing ability they observed in participants. Conversely, Berryman and associates (2010) found changes in s$\dot{V}O_{2max}$ (4.2%, ES: 0.43-0.49) alongside improvements in RE (4-7%, ES: 1.01), moderate increases in power output, and no change in $\dot{V}O_{2max}$ scores. Beattie and co-workers (2017) credited the change in s$\dot{V}O_{2max}$ they observed (20 weeks: 3.5%, ES: 0.7) to the accumulation of improvements in RE, $\dot{V}O_{2max}$ and anaerobic factors, however these were not sufficiently large enough to provide a significant group x time interaction. Millet and colleagues (2002) found notable improvements in RE (7.4%, ES: 1.14), however changes in RE could not explain the changes observed in s$\dot{V}O_{2max}$ ($r=-0.46$, $p=0.09$). It may also be the case that longer periods of ST are required before an improvement in s$\dot{V}O_{2max}$ is detected, as studies showing an improvement (2.6-4.0%, ES: 0.57-0.9) from baseline lasted 14 weeks or more (Beattie et al., 2017; Millet et al., 2002), and studies showing little change tended to be 6-8 weeks in duration (Bertuzzi et al., 2013; Karsten et al., 2016; Mikkola et al., 2007).

The conflicting results could also be explained by the inconsistency in methods used to define s$\dot{V}O_{2max}$. A number of different protocols and predictive methods have been suggested to assess s$\dot{V}O_{2max}$ (Billat and Koralsztein, 1996), including determination from the $\dot{V}O_2$-speed relationship (Daniels et al., 1984) and the peak running speed attained during a maximal test using speed increments to achieve exhaustion (Billat et al., 1994; Noakes, 1988). All studies that measured s$\dot{V}O_{2max}$ in this review did so via an incremental run to exhaustion progressed using speed. s$\dot{V}O_{2max}$ was taken as the highest speed that could be maintained for a full 60 s stage (Berryman et al., 2010; Bertuzzi et al., 2013; Mikkola et al., 2007), an average of the final 30 s (Giovanelli et al., 2017; Karsten et al., 2016), the mean speed in the final 120 s (Vikmoen et al., 2016), or the minimum speed that elicited $\dot{V}O_{2max}$ (Beattie et al., 2017; Millet et al., 2002). Although a direct approach to the measurement of s$\dot{V}O_{2max}$ has been recommended (Billat and Koralsztein, 1996), due to the speed increments (0.5-1.0 $km \cdot h^{-1}$) used in these investigations, this may not provide sufficient sensitivity to detect a change following a short- to medium-term intervention. Damasceno and associates (2015) calculated s$\dot{V}O_{2max}$ using a more precise method based upon the fractional time participants reached through the final stage of the test multiplied by the increment rate. This perhaps provided a greater level of accuracy that allowed the authors to identify the differences in changes which existed between the groups. Taken together, there is weak evidence that s$\dot{V}O_{2max}$ can be improved following a ST intervention, despite constituent physiological qualities often exhibiting change. Differences in the protocols used to determine s$\dot{V}O_{2max}$ makes comparison problematic, however a more precise measurement of s$\dot{V}O_{2max}$ that accounts for partial completion of a final stage is likely to provide the sensitivity to identify subtle changes that may occur.

Critical speed also represents a potentially valuable determinant of distance running performance, which has currently received very little attention in the research. Evidence from studies using untrained participants has demonstrated that the total amount of work that can be performed above critical power during high-intensity cycling exercise is improved (35-60%) following 6-8 weeks of RT (Bishop and Jenkins, 1996; Sawyer et al., 2014). Future investigations should therefore address the dearth in literature around how ST might positively influence parameters related to the critical speed model (Denadai and Greco, 2017b).

2.5.4.4 Blood Lactate Markers

In contrast to RE, ST appears to have little impact upon BL markers. This is quite surprising as an improvement in RE should theoretically result in an enhancement in speed for a fixed BL concentration. This suggests that adaptations to RE can occur independently to changes in metabolic markers of performance. An absence of change in BL also implies that ST does not alter anaerobic energy contribution during running, thus assuming aerobic energy cost of running is reduced following ST, it can be inferred that total energy cost (aerobic plus anaerobic energy) is also likely to be reduced. Previous studies have shown as little as six weeks of endurance training can improve BL levels or the speed corresponding to an arbitrary BL value in runners (Billat et al., 2004; Carter et al., 1999; Tanaka et al., 1984). The intensity of training is important to elicit improvement in BL parameters (Londeree, 1997), therefore it appears that the running training prescription may have been insufficient to stimulate improvements, or the training status of participants meant a longer period was required to realise a meaningful change. In addition, the inter-session reliability of BL measurement between 2-4 $mMol\cdot L^{-1}$ is ~0.2 $mMol\cdot L^{-1}$ (Pfitzinger and Freedson, 1998; Winter et al., 2006), therefore over a short study duration this metric may not provide sufficient sensitivity to detect change.

Training at an intensity above the LT is likely to result in a reduction in the rate of BL production (and therefore accumulation), or an improved lactate clearance ability from the blood (Jones and Carter, 2000). Short duration high-intensity bouts of activity generate high levels of BL so drive metabolic adaptations that can result in an improvement in performance (Burgomaster et al., 2006; Harmer et al., 2000; Jacobs et al., 1987). Studies that have utilised high-repetition, low-load RT in endurance athletes therefore have the potential to produce high BL concentrations so may provide an additional stimulus to improve performance via BL parameters. This theory is supported by works that have demonstrated improvements in BL-related variables in endurance athletes following an intervention that uses a strength-endurance style of conditioning with limited rest between sets (Hamilton et al., 2006; Marcinik et al., 1991; Mikkola et al., 2011). The ST prescription in the studies reviewed was predominantly low-repetition, high-intensity RT or PT, which is unlikely to have provided a metabolic environment sufficient to directly enhance adaptations related to BL markers.

2.5.4.5 Time Trial Performance

Physiological parameters such as $\dot{V}O_{2max}$, s$\dot{V}O_{2max}$, RE and LT are clearly important determinants that can be quantified in a laboratory, however for a runner, TT performance possesses a far higher degree of external validity. Similar improvements in TT performance were observed for middle-distance events (3-5%, ES: 0.4-1.0) and long-distance events up to 10 km (2-4%, ES: 1.06-1.5). In the majority of these studies, time-trials took place in a similar environment and under comparable conditions to a race, therefore these findings have genuine applicability to ‘real-life’ scenarios. These improvements are likely to be a consequence of significant enhancements in one or more determinants of performance. Interestingly, Damasceno and co-authors (2015) found an improvement in 10 km TT performance due to the attainment of higher speeds in the final 3 km, despite observing no change in RE during a separate assessment. This suggests that greater levels of muscular strength may result in lower levels of relative force production per stride, thereby delaying recruitment of higher threshold muscle fibres and thus providing a fatigue resistant effect (Hayes et al., 2004). This subsequently manifests in a superior performance during the latter stages of long-distance events (Damasceno et al., 2015).

Four studies observed no difference in performance change compared to a CG (Berryman et al., 2010; Schumann et al., 2015; Schumann et al., 2016; Spurrs et al., 2003; Vikmoen et al., 2017). Vikmoen and colleagues (2017) attributed a lack of effect in their 40 min TT to the slow running speed caused by the 5.3% treadmill inclination used in the test. This was also the only study to use a treadmill set to a pre-determined speed that participants could control once the test had commenced. The absence of natural self-pacing may therefore have prevented participants achieving their true potential on the test. Spurrs et al. (2003) and Berryman et al. (2010) both found improvements in 3 km performance compared to a pre-training measure of a comparable magnitude to other studies (2.7-4.8%, ES: 0.13-0.46), however changes were not significantly different to a CG, suggesting ST provided no additional benefit or there was a practice effect associated with the test.

It could be possible that enhancement of physiological qualities in some studies could be attributed to RT being positioned immediately after low-intensity, non-depleting running sessions (Baar, 2014). This arrangement of activities in concurrent training programmes has been shown to provide a superior stimulus for endurance adaptation compared to performing separate sessions, and without compromising the signalling response regulating strength gains (Coffey et al., 2009; Wang et al., 2011). This however appears not to be the case, as most studies reported ST activities took place on different days to running sessions (Bertuzzi et al., 2013; Damasceno et al., 2015; Skovgaard et al., 2014) or were at least performed as separate sessions within the same day (Beattie et al., 2017; Giovanelli et al., 2017; Johnston et al., 1997; Mikkola et al., 2007; Spurrs et al., 2003; Vikmoen et al., 2017). Only three studies performed ST and running immediately after one another, with one positioning PT before running (Ramirez-Campillo et al., 2014) and one lacking clarity on sequencing (Turner et al., 2003). Schumann and colleagues (2015, 2016) observed no additional benefit to both strength and endurance outcomes compared to a running only group, when ST was performed immediately following an incremental running session (65-85% maximal HR), citing residual fatigue that compromised quality of ST sessions as the reason.

2.5.4.6 Anaerobic Running Performance

Tests for pure maximal sprinting velocity (20-30 m) were used in three studies (Mikkola et al., 2007; Paavolainen et al., 1999a; Ramirez-Campillo et al., 2014) and showed improvements (1.1-3.4%) following ST in every case. This confirms results from previous studies that have shown sprinting performance can be positively affected by a ST intervention in shorter-distance specialists (Blazevich and Jenkins, 2002; Kamandulis et al., 2012; Satkunskiene et al., 2009). This finding has important implications for distance runners, as competitive events often involve mid-race surges and outcomes are frequently determined in sprint-finishes, particularly at an elite level (Hanley, 2014; 2015;

Sandford et al., 2017; Tucker et al., 2006). Middle-distance runners also benefit from an ability to produce fast running speeds at the start of races (Turnes et al., 2014), therefore improving maximum speed allows for a greater 'anaerobic speed reserve' (Bundle et al., 2003), resulting in a lower relative work-rate, and thus decreasing anaerobic energy contribution (Jung, 2003). Interestingly, endurance training in cyclists has been shown to improve critical power (Vanhatalo et al., 2011) but reduce work capacity for short duration exercise (Jenkins and Quigley, 1992; Vanhatalo et al., 2008). It is unknown whether long-term aerobic training has a similar effect on anaerobic running qualities, however ST offers a strategy to avoid this potential negative consequence.

The sMART provides an indirect measure of anaerobic and neuromuscular performance, and has a strong relationship (r=0.85) to s$\dot{V}O_{2max}$ (Paavolainen et al., 2000). The sMART is particularly relevant to middle-distance runners because it requires athletes to produce fast running speeds under high-levels of fatigue caused by the acidosis and metabolites derived from glycolysis (Rusko, 1996). Both studies that included this test observed significant improvements in sMART (1.1-3.4%), which can be attributed to changes observed in neuromuscular power as a result of the ST intervention (Mikkola et al., 2007; Paavolainen et al., 1999a). One study showed no alteration in the predicted distance achieved on an anaerobic running test following six weeks of HRT, however the validity and reliability of the test was questioned by the authors (Karsten et al., 2016). Performance on a 30 s Wingate test was also unchanged following eight weeks of running training combined with HRT in recreational participants (Damasceno et al., 2015). This finding perhaps underlines the importance of selecting tests which are specific to the training which has been performed in the investigation.

2.5.4.7 Strength Outcomes

Changes in strength outcomes were evident in most studies despite all but one (Mikkola et al., 2007) observing no change in body mass. Since strength changes can be ascribed to both neurological and morphological adaptations (Folland and Williams, 2007), it is therefore likely that improvements are primarily underpinned by alterations in intra- and inter-muscular co-ordination. It is also known that initial gains in strength in non-strength trained individuals are the consequence of neural adaptations rather than structural changes (Kraemer et al., 1996). An improvement in force producing capability is perhaps expected in individuals who have little or no ST experience (Sale, 1988), however concurrent regimens of training have consistently been shown to attenuate strength-related adaptation (Wilson et al., 2012b).

The seminal paper published by Hickson was the first to identify the potential for endurance exercise to mitigate strength gains, when both training modalities were performed concurrently within the same programme (Hickson, 1980). Follow-up investigations have since shown mixed results (Kraemer et al., 1995; Lundberg et al., 2013; McCarthy et al., 1995; McCarthy et al., 2002; Ronnestad et al., 2012; Sale et al., 1990), but evidence from this review clearly demonstrates that, for the distance runner at least, strength-related improvements are certainly possible following a concurrent period of training. Nevertheless, the study designs adopted by the works under review did not include a strength-only training group, thus it is not possible to determine whether strength adaptation was in fact negated under a concurrent regimen. One study using well-trained endurance cyclists with no ST experience, observed a blunted strength response in a group who added ST to their endurance training compared to a group who only performed ST (Ronnestad et al., 2012). Based upon this finding and other similar observations (Chtara et al., 2008; Hennessy and Watson, 1994; Kraemer et al., 1995) it seems likely that although distance runners can significantly improve their strength using a concurrent approach to training, strength outcomes are unlikely to be maximised. Moreover, the degree of interference with strength-adaptation also appears to be exacerbated when volumes of endurance training are increased and the duration of concurrent training programmes is longer (Baar, 2014; Wilson et al., 2012b).

2.5.4.8 Body Composition

RT performed 2-3 times per week is associated with increases in muscle cross-sectional area as a principal adaptation (Hakkinen, 1989). Although gains in gross body mass may appear to be an unfavourable outcome for distance runners, the addition of muscle mass to proximal regions of the lower limb (i.e. gluteal muscles) should theoretically provide an advantage, via increases in hip extension forces, minimising moment of inertia of the swinging limb, and reducing absolute energy usage (Fletcher and MacIntosh, 2017). It is somewhat surprising that virtually all studies demonstrated an absence of change in body mass, fat-free mass, lean muscle mass and limb girths. Other than one investigation (Beattie et al., 2017), the duration of the studies that observed no effect on measures of body composition was <14 weeks, suggesting this may not have been sufficiently long to demonstrate a clear hypertrophic response. There is also a possibility that small increases in muscle mass within specific muscle groups (e.g. gluteals) were present, and contributed to the improvements observed in RE, but these may not have been detectable using a gross measure of mass. Evidence for this may have occurred in the Schumann et al. (2015, 2016) study, who observed increases in total lean mass (3%) despite noting no significant change in body mass or cross-sectional area of the vastus lateralis compared to baseline measures.

The interference effect observed during concomitant integration of endurance and ST as part of the same programme may also provide an explanation for the lack of change in measures of mass. Following a bout of exercise, a number of primary and secondary signalling messengers are up regulated for 3-12 h (Yang et al., 2005), which initiate a series of molecular events that serve to activate or suppress specific genes. The signalling messengers that are activated, relate to the specific stress which is imposed on the physiological systems involved in an exercise bout. ST causes mechanical perturbation to the muscle cell, which elicits a multitude of signalling pathways that lead to a hypertrophic response (Spiering et al., 2008). In particular, the secretion of insulin-like growth factor-1 as a result of intense muscular contraction is likely to cause a cascade of signalling events which increase activity of phosphoinositide-3-dependent kinase (Pl-3k) and the mammalian target of Rapamycin (mTOR) (Glass, 2005; Song et al., 2005; Vary, 2006). There is strong evidence that mTOR is responsible for mediating skeletal muscle hypertrophy via activation of ribosome proteins which up regulate protein synthesis (Bodine, 2006). Prolonged exercise bouts, such as those associated with endurance training, activate metabolic signals related to energy depletion, uptake and release of calcium ions from the sarcoplasmic reticulum and oxidative stress in cells (Irrcher et al., 2003). Adenosine monophosphate activated kinase (AMPK) is a potent secondary messenger which functions to monitor energy homeostasis (Hardie and Sakamoto, 2006) and when activated, modulates the release of peroxisome proliferator co-activator-1α, which along with calcium-calmodulin-dependent kinases increase mitochondrial function to enhance aerobic function (Horman et al., 2002; Irrcher et al., 2003; Rose and Hargreaves, 2003). Crucially though, AMPK also acts to inhibit the Pl-3k/mTOR stage of the pathway via activation of the tuberous sclerosis complex thereby suppressing the ST induced up regulation of protein synthesis (Baar, 2006; Nader, 2006). This conflict arising at a molecular signalling level therefore appears to impair the muscle fibre hypertrophy response to ST and attenuate increases in body mass (Nader, 2006).

2.5.4.9 Muscle-Tendon Interaction Mechanisms

The potential mechanisms for the positive changes observed in physiological parameters underpinning running performance were directly investigated in three studies (Albracht and Arampatzis, 2013; Fletcher et al., 2010; Pellegrino et al., 2016), and were inferred from gait measures (Giovanelli et al., 2017; Millet et al., 2002; Paavolainen et al., 1999a; Saunders et al., 2006; Spurrs et al., 2003) and strength outcomes in others. It is well-documented that muscle-tendon unit stiffness correlates well with RE (Arampatzis et al., 2006; Dalleau et al., 1998; Dumke et al., 2010; Rogers et al., 2017). Tendons are also highly adaptable to mechanical loading and have been shown to increase in stiffness in response to HRT and PT (Albracht and Arampatzis, 2013; Foure et al., 2010; Kubo et al., 2002). Despite observing no statistical effect for HRT on RE, Fletcher and colleagues (2010) found a relationship between the change in RE and the changes observed in Achilles tendon stiffness. Notwithstanding these associations, it is likely that improvements in RE are a consequence of the interaction between adaptations to tendon properties and improvements in motor unit activation which influence behaviour of force-length-velocity properties of muscles (Fletcher and MacIntosh, 2017). It tends to be assumed that improved tendon stiffness allows the body to store and return elastic energy more effectively, which results in a reduction in muscle energy cost due to a greater contribution from the elastic recoil properties of tendons (Kyrolainen et al., 2001). Indeed, authors of studies in the present review have argued that the improvements observed in RE following a period of ST are due to an enhanced utilisation of elastic energy during running (Giovanelli et al., 2017;

Millet et al., 2002; Paavolainen et al., 1999a; Spurrs et al., 2003). An alternative proposal, based upon more recent evidence, suggests the Achilles tendon provides a very small contribution to the total energy cost of running therefore improvements in stiffness provide a negligible reduction in energy cost (Fletcher et al., 2013; Fletcher and MacIntosh, 2015). Instead, a tendon with an optimal stiffness contributes to improving RE by minimising the magnitude and velocity of muscle shortening, thus allowing muscle fascicles to optimise their length and remain closer to an isometric state (Fletcher and MacIntosh, 2017). A reduction in the amount and velocity of fibre shortening therefore reduces the level of muscle activation required and hence the energy cost of running (Fletcher et al., 2013).

The improvements observed in maximal and explosive strength, which can be attributed to increases in motor unit recruitment and firing frequency, enable the lower limb to resist eccentric forces during the early part of ground contact (Sale, 1988) and thus contribute to the attainment of a near isometric state during stance. As the force required to sustain speed during distance running performance is submaximal, the level of motor unit activation needed can be minimised when fascicles contract isometrically (Fletcher and MacIntosh, 2017). This enables the Achilles tendon in particular to accommodate a greater proportion of the muscle-tendon unit length change during running thereby reducing metabolic cost (Fletcher and MacIntosh, 2015). Variables which provide an indirect measure of the neuromuscular systems ability to produce force rapidly and utilise tendon stiffness were found to improve in other studies that showed improvements in running performance and/or key determinants (Berryman et al., 2010; Mikkola et al., 2007; Millet et al., 2002; Paavolainen et al., 1999a; Ramirez-Campillo et al., 2014; Storen et al., 2008). However, some studies found improvements in running-related parameters despite observing no alterations in jump performance (Beattie et al., 2017; Mikkola et al., 2007; Pellegrino et al., 2016; Saunders et al., 2006; Turner et al., 2003), RFD (Giovanelli et al., 2017; Saunders et al., 2006; Spurrs et al., 2003), or stiffness (Beattie et al., 2017; Damasceno et al., 2015; Millet et al., 2002) illustrating that measures were insufficiently sensitive to detect change, or a combination of mechanisms are likely to be contributing towards the enhancements observed.

HRT causes a shift in muscle fibre phenotype, from the less efficient myosin heavy chain (MHC) IIx to more oxidative MHC IIa, (Staron et al., 1994; Staron et al., 1990). A higher proportion of MHC IIa has been shown to relate to better RE (Hunter et al., 2015; Kyrolainen et al., 2003; Pellegrino et al., 2016), however whether changes to MHC properties as a result of ST contribute to an improvement in RE and performance remains to be determined. One previous study provided evidence that four weeks of sprint running (30 s bouts) improve RE and also the percentage of MHC IIx (Iaia et al., 2009), however the absence of endurance training may partly explain the shift in phenotype. Over a longer period (six weeks), Pellegrino and co-workers (2016) found no measurable changes in MHC isoforms following a PT intervention despite a significant improvement in 3 km TT performance, suggesting that a contribution from this mechanism is unlikely for distance running.

It could also be speculated that improvements in RE due to improved strength might have resulted in subtle changes to running kinematics, thus enabling participants to perform less work for a given submaximal speed (Johnston et al., 1997). There is currently little direct support for this conjecture, however previous work has shown that running technique is an important component of RE (Folland et al., 2017; Williams and Cavanagh, 1987), and improving hip strength can reduce undesirable frontal and transverse plane motion in the lower limb during running (Ferber et al., 2011; Snyder et al., 2009). One study in this review did observe a reduction in EMG amplitude in the superficial musculature of the lower limb following ST, however this was not accompanied by an improvement in RE (Bonacci et al., 2011). This suggests that favourable adaptations in neuromuscular control do not necessarily translate to reducing the metabolic cost of running. Additionally, two studies showed significant increases (3.0-4.4%) in ground contact time during submaximal running after a ST intervention (Ferrauti et al., 2010; Giovanelli et al., 2017), however only Giovanelli and colleagues (2017) found a corresponding improvement in RE. Several papers have demonstrated an inverse relationship between RE and ground contact times (Chapman et al., 2012; Di Michele and Merni, 2014; Folland et al., 2017), since a lower peak vertical force is required to generate the same amount of impulse during longer compared to short ground contacts (Fletcher and MacIntosh, 2017). Although there is currently minimal evidence to suggest a ST intervention increases ground contact time during sub-maximal running, this mechanism may in part explain the improvements in RE.

2.5.4.10 Strength Training Modality and Exercise Selection

The works included in this review used a variety of ST modalities, however the most effective type of training is currently difficult to discern. Adaptations are specific to the demands placed upon the body, therefore it would be expected that HRT, EST and PT produce somewhat different outcomes (Crewther et al., 2005). This can be observed in the study by Berryman and co-workers (2010), who observed larger improvements in explosive concentric power in a group following an ERT programme compared to a group who used PT. The opposite result occurred for the CMJ, which places a greater reliance on a plyometric action; the PT group displayed greater improvements than the ERT group (Berryman et al., 2010). HRT, which is characterised by slow velocities of movement, is likely to improve agonist muscle activation via enhanced recruitment of the motor neuron pool, whereas ERT, which involves lighter loads being moved rapidly, tends to enhance firing frequency and hence improve RFD (Folland and Williams, 2007; Sale, 1988). PT develops properties related to the stretch-shortening cycle function (Markovic and Mikulic, 2010), and uses movements patterns which closely mimic the running action (e.g. hopping and skipping). It is therefore likely that although a variety of ST methods are capable of improving physiological parameters relating to distance running performance, the mechanisms underpinning the response may differ.

In less strength-trained individuals, such as those used in the studies reviewed, any novel ST stimulus is likely to provide a sufficient overload to the neuromuscular system to induce an adaptation in the short-term (Cormie et al., 2010a). This is perhaps why ST is effective even in highly-trained distance runners (Millet et al., 2002; Ramirez-Campillo et al., 2014; Saunders et al., 2006). Studies that have attempted to compare ST techniques in distance runners have generally shown HRT to be superior to ERT or a mixed methods approach at improving aerobic parameters (Barnes et al., 2013b; Guglielmo et al., 2009) and maximal anaerobic running speed (Mikkola et al., 2011). PT has also shown superiority to ERT for improvement of RE in moderately trained runners (Berryman et al., 2010). Other investigations have found no differences in the physiological changes between groups using HRT, ERT or a mixture of modalities (Mikkola et al., 2011; Taipale et al., 2013). A number of studies have also shown HRT and/or ERT to be more beneficial to a muscular endurance style of ST (Piacentini et al., 2013; Sedano et al., 2013; Taipale et al., 2010; Taipale et al., 2014; Taipale et al., 2013). The addition of whole body vibration to RT also provides no extra benefit (Bertuzzi et al., 2013). Although ERT and PT may have more appeal compared to HRT due to their higher-level of biomechanical similarity to running, an initial period of HRT is likely to provide an advantage long-term by way of reducing injury risk (Lauersen et al., 2014) and eliciting a more pronounced training effect (Cormie et al., 2010b; James et al., 2018). Taken together, it seems that long-term, a mixed modality approach to ST is most effective, as this provides the variety and continual overload required to ensure the neuromuscular system is constantly challenged. One study that used a longer intervention period lends support to this notion, as significant improvements were observed in strength and physiological measures after 20- and 40-weeks with a periodised methodology that used several types of ST (Beattie et al., 2017). Further research is required to ascertain the long-term benefits of various ST modalities and the relative merits of different approaches to sequencing and progressing these modalities.

As discussed in Section 2.5.4.1, the exercises selected in a ST programme can potentially influence the magnitude of neuromuscular adaptation and thus the impact on physiological determinants of performance. Exercises using free weights, which require force to be generated from the leg extensor muscles in a close-kinetic chain position, are the most likely to positively transfer to running performance (Gamble, 2006). Examples of RT exercises commonly used include: barbell squat, deadlifts, step-ups and lunging movement patterns (Beattie et al., 2017; Bertuzzi et al., 2013; Giovanelli et al., 2017; Johnston et al., 1997; Karsten et al., 2016; Skovgaard et al., 2014; Storen et al., 2008). Isometric HRT may also have value for the plantarflexors (Albracht and Arampatzis, 2013). ERT, by its very nature, should avoid a deceleration phase, therefore exercises such as squat jumps and Olympic weightlifting derivatives should be utilised (Beattie et al., 2017; Berryman et al., 2010). To maximise transfer to distance running performance, particularly at faster speeds, PT exercises should exhibit short ground contact times (<0.2 s) (Giovanelli et al., 2017; Johnston et al., 1997) which approximates the contact times observed in competitive middle- (Hayes and Caplan, 2012) and long-distance running (Hasegawa et al., 2007), and encourages a rapid excitation-contraction coupling sequence and improved musculotendious stiffness (Giovanelli et al., 2017; Millet et al., 2002; Paavolainen et al., 1999a; Spurrs et al., 2003). Exercises which possess a low to moderate eccentric demand such as depth jumps (DJ) from a 20-30 cm box, skipping, hopping, speed bounding appear most suitable (Beattie et al., 2017; Berryman et al., 2010; Bonacci et al., 2011; Paavolainen et al., 1999a; Saunders et al., 2006; Spurrs et al., 2003).

2.5.4.11 Intra-Session Variables

For non-strength trained individuals, exercise prescription and gradual progression is important to avoid injury and overtraining (Kraemer and Ratamess, 2004). Most studies initially used 1-2 sets and progressed to 3-6 sets over the course of the intervention period for HRT, ERT and PT, which appears appropriate to circumvent these risks. Several studies utilised a low (3-5) repetition range in every HRT session (Ferrauti et al., 2010; Karsten et al., 2016; Piacentini et al., 2013; Storen et al., 2008) at loads which approached maximum (≥ 80% 1RM or repetition failure), but did not observe superior benefits compared to investigations that prescribed RT at moderate loads (60-80% 1RM) and higher repetition ranges (5-15 repetitions). Sets were performed to RM in a number of studies (Damasceno et al., 2015; Ferrauti et al., 2010; Johnston et al., 1997; Skovgaard et al., 2014; Storen et al., 2008; Vikmoen et al., 2016; Vikmoen et al., 2017), which was likely employed as a means of standardising the intensity of each set in the absence of 1RM data for participants (Dankel et al., 2017a). Performing sets that lead to repetition failure induces a high level of metabolic and neuromuscular fatigue, which may delay recovery (Izquierdo et al., 2006). Although training to repetition failure may be more important than the load lifted for inducing a hypertrophy response (Morton et al., 2016), this is both unfavourable and unnecessary to optimise gains in strength compared to a non-repetition failure strategy (Davies et al., 2016). Not working to repetition failure also appears to become a more important feature of RT as ST status increases (Davies et al., 2016). Participants were often instructed to move the weights as rapidly as possible when performing the concentric phase of RT exercises, which increases the likelihood of maximising neuromuscular adaptations (Pareja-Blanco et al., 2014). PT is characterised by high eccentric forces compared to running and RT, therefore repetitions per set were typically low (4-10 repetitions). Total foot contacts progressed from 30-60 repetitions in the first week of an intervention up to 110-228 repetitions after 6-9 weeks (Paavolainen et al., 1999a; Pellegrino et al., 2016; Spurrs et al., 2003; Turner et al., 2003). Plyometric exercises were all performed without additional external resistance in all but one study (Paavolainen et al., 1999a) and in many cases a short ground contact time (Bonacci et al., 2011; Saunders et al., 2006; Turner et al., 2003) and maximal height (Berryman et al., 2010; Bonacci et al., 2011) were cued to amplify the intensity. An inter-set recovery period of 2-3 minutes was typical for HRT, ERT and PT, which is in line with recommendations for these training techniques (Kraemer and Ratamess, 2004). Where SpT was incorporated into ST programmes, repetition distances were short (20-150 m) and performed at or close to maximal running speed (Millet et al., 2002; Paavolainen et al., 1999a; Skovgaard et al., 2014).

2.5.4.12 Inter-Session Variables

The majority of studies that demonstrated improvements in running physiology scheduled ST 2-3 times per week, which is in line with the guidelines for non-strength trained individuals (Kraemer and Ratamess, 2004). One study used just one session per week (ERT or PT) and achieved moderate improvements in strength outcomes and RE after eight weeks of training (Berryman et al., 2010). Beattie and associates (2017) observed small improvements (ES: 0.3) in RE using a single ST session (mixed activities) each week for 20 weeks, however the participants had already experienced moderate improvement (ES: 1.0) in this parameter using a twice weekly programme in the 20 weeks prior. For well-trained runners who complete 8-13 running sessions per week (Paavolainen et al., 1999a; Saunders et al., 2006), it would be useful to establish the minimal ST dosage required to elicit a beneficial effect to reduce the risk of overtraining. Equally, for the recreational runner, ST may take up valuable leisure time that could be spent running, therefore identifying the optimal volume and frequency of ST to achieve an improvement in performance would be desirable. A previous meta-analysis indicated that 2 or 3 sessions per week provides a large effect on strength, but for the non-strength trained individual, three sessions is superior to two sessions per week (Rhea et al., 2003). More recently, a weak relationship was established between improvement in RE and weekly frequency of ST sessions in 311 endurance runners (Denadai et al., 2017). This suggests that higher weekly volumes of ST would not necessarily provide greater RE improvements, therefore two sessions per week is likely to be sufficient (Denadai et al., 2017).

Given the volume of endurance training participants were exposed to and the duration of each study, it seems likely that an attenuation of strength-related adaptation would have occurred. To minimise this interference phenomenon, it is therefore recommended that a recovery period of >3 h is provided following high-intensity running training before ST takes place (Baar, 2014). In many studies running training and ST took place on different days (Beattie et al., 2017; Bertuzzi et al., 2013; Damasceno et al., 2015; Giovanelli et al., 2017; Skovgaard et al., 2014), and several papers noted a gap of >3 h between running and ST on the same day (Johnston et al., 1997; Mikkola et al., 2007; Storen et al., 2008; Vikmoen et al., 2016; Vikmoen et al., 2017). This feature of concurrent training prescription therefore appears important in ensuring sufficient strength-adaptations are realised but without compromising running training. Although there is very little evidence that the dosage of ST prescribed impaired any endurance-related adaptations, recent work has highlighted that acute bouts of RT may cause fatigue sufficient to impair subsequent running performance, which long-term may result in sub-optimal adaptation (Doma et al., 2017). It is therefore recommended that this potential fatigue is accounted for by allowing at least 24 h recovery between a ST session and an intensive running session (Beattie et al., 2017; Bertuzzi et al., 2013; Damasceno et al., 2015; Skovgaard et al., 2014).

The results provide compelling evidence that a relatively short period (six weeks) of ST can enhance physiological qualities related to distance running performance. Improvements in RE (Guglielmo et al., 2009) and 10 km TT performance (Skovgaard et al., 2014) have also been shown in as little as four weeks. A relationship between intervention duration and improvement in RE has previously been reported (Denadai et al., 2017), suggesting that longer periods of ST provide a larger benefit. The same may be true for s$\dot{V}O_{2max}$, however more research using longer periods of ST is required to establish if this is indeed the case. The benefits to performance also seem to be dependent on study duration as most short interventions (six weeks) tended to produce small TT improvements (2.4-2.7%, ES: 0.13-0.4) (Pellegrino et al., 2016; Ramirez-Campillo et al., 2014; Spurrs et al., 2003), whereas longer programmes (8-11 weeks) resulted in moderate or large performance effects (3.1-5.5%, ES: 0.67-1.50) (Paavolainen et al., 1999a; Skovgaard et al., 2014; Vikmoen et al., 2016). It would seem reasonable to assume that highly-trained distance runners would require a higher volume of ST to achieve the same benefit as less experienced runners, however this does not appear to be the case. Relatively short (6-9 weeks) periods of ST improved RE and TT performance to a similar extent in highly-trained individuals (Ramirez-Campillo et al., 2014; Saunders et al., 2006) and recreational runners (Pellegrino et al., 2016; Piacentini et al., 2013; Turner et al., 2003). It is therefore recommended that future investigations use periods of ten weeks or longer to provide further insight into how ST modalities may impact physiological parameters long-term in different types of distance runner.

The time of year or phase of training when the research was conducted was not reported in the majority of studies. Several papers indicated that the intervention formed part of an off-season preparation period (Fletcher et al., 2010; Mikkola et al., 2007; Millet et al., 2002; Paavolainen et al., 1999a; Piacentini et al., 2013), but others scheduled the intervention within the competition period (Ramirez-Campillo et al., 2014; Vikmoen et al., 2016; Vikmoen et al., 2017). Based upon the literature reviewed, it is currently not possible to provide specific recommendations for ST in different phases of a runners training macrocycle, as most studies found at least some physiological or performance benefits to concurrent training. Importantly though, evidence suggests that choosing to exclude ST following a successful intervention period results in a detraining effect which causes improvements to return to baseline levels within six weeks (Karsten et al., 2016). The 40 week intervention conducted by Beattie and colleagues (2017) provides evidence that reducing ST volume from two sessions per week (both with a lower limb HRT emphasis) during the preparatory phase to one weekly session (ERT and PT emphasis) during the in-season racing period is sufficient to at least maintain previous strength and physiological gains. This finding corroborates with a maintenance effect observed in cyclists (Ronnestad et al., 2010; Ronnestad et al., 2015) and soccer players (Ronnestad et al., 2011) showing one ST session per week is sufficient to preserve the strength qualities developed during a preceding phase of training. Therefore, runners can decrease ST volume from 2-3 sessions per week (each with a lower limb focus) in preparatory phases of training to a single session each week during the competitive season without fearing a loss of adaptation as a consequence of the reduction in training density.

It is currently uncertain what volume and intensity of running and ST are most likely to avoid the interference effect associated with concurrent training practices. One option to minimise attenuation of strength development is to organise activities into periods that concentrate on developing either strength or endurance adaptation (Garcia-Pallares and Izquierdo, 2011). This polarised approach to planning seems unnecessary and counterintuitive for distance runners who generally possess little ST experience, therefore require a minimal stimulus to create an adaptation. Indeed, studies that replaced running training with ST (Mikkola et al., 2007; Paavolainen et al., 1999a; Skovgaard et al., 2014) found no greater benefit than those which included ST in a supplementary manner.

2.5.4.13 Training Supervision

In most studies, the ST routine was supervised and tightly monitored, however similar controls were often absent for the running training participants performed. It seems reasonable to assume that any errors in participants training logbooks would be similar across intervention and CGs, however validity of findings would be improved if the running component of training had been more tightly defined. Where supervision of the ST exercises was not included (Turner et al., 2003) or only included for the first two weeks (Giovanelli et al., 2017), strength measures did not improve following the intervention period. This indicates that a suitably qualified coach is an important feature of a ST programme for a distance runner who lacks ST experience.

2.5.4.14 Limitations

In addition to the limitations already highlighted in this review, there are other weaknesses that should be acknowledged. For many of the studies reviewed, calculation of an ES was possible for the variables measured, which provides insight into the meaningfulness and substantiveness of results. However, despite the qualitative nature of this review, interpretation of findings was predominantly based upon reported probability values, which can be misleading due to low sample sizes and the heterogeneity in the pool of participants studied. A relatively large number of studies have been included in this review, however several parameters (e.g. s$\dot{V}O_{2max}$ and BL) were measured in only a small number of studies, which increases the possibility that false conclusions may be drawn.

There was also a lack of detail concerning several important confounding variables in studies, such as the nature of running training prescription and participant's previous experience in ST. All but seven studies (Albracht and Arampatzis, 2013; Karsten et al., 2016; Millet et al., 2002; Paavolainen et al., 1999a; Piacentini et al., 2013; Schumann et al., 2015; Schumann et al., 2016; Turner et al., 2003) identified that participants had not been engaged in a programme of ST for at least three months prior to the study commencing. Although it is perhaps unlikely that participants in these seven studies were strength-trained, this cannot be discounted and may therefore have influenced findings in these investigations.

2.6 Acute Effects of Loaded Conditioning Activities on Middle- and Long-Distance Performance

2.6.1 Aim

To acutely optimise middle- and long-distance performance, it is well-established that an active warm-up should be included in an athlete's preparation routine (Bishop, 2003). Research has tended to focus on 'priming' strategies, involving high-intensity intermittent or continuous exercise designed to induce specific cardiovascular and metabolic adjustments, which subsequently augment the $\dot{V}O_2$ kinetic response (see Section 2.3.6) during the early stages of exercise, and thus performance outcomes (Bailey et al., 2009; Burnley et al., 2005; Burnley and Jones, 2007; Jones et al., 2003b).

Conversely, for athletic performances that require high levels of power production, such as jumps and sprints, a plethora of research has been conducted investigating various preconditioning stimuli designed to potentiate the neuromuscular system, and enhance performance in these tasks (Maloney et al., 2014; Seitz and Haff, 2016; Wilson et al., 2013). Although it is well-established that physiological parameters and performance can benefit following a period of ST in middle- and long-distance athletes (Beattie et al., 2014; Berryman et al., 2017), the possibility of using a LCA to acutely enhance middle- and long-distance related outcomes has only been explored recently (Barnes et al., 2015; Chorley and Lamb, 2017; Silva et al., 2014). A LCA involves utilising a high-intensity resistance exercise or adding load to a movement akin to the sports skill itself, in order to elicit a short-term enhancement in neuromuscular function, known as PAP. The aim of this section is therefore to consider whether a LCA can provide an acute potentiation of middle- and long-distance performance from a theoretical and evidence-based perspective, and provide practical recommendations that can be applied to the design of a subsequent study in this thesis.

2.6.2 Priming Activity

Studies have typically shown that a warm-up which includes a bout of high-intensity exercise (60-85% of peak power output) lasting 3-6 min is sufficient to positively influence endurance performance (Bailey et al., 2009; Gurd et al., 2006; Mattioni Maturana et al., 2017). Several studies have also investigated the effects of high-intensity intermittent and single sprint approaches to enhancing performance or the $\dot{V}O_2$ response at the onset of exercise (Bishop et al., 2003; Burnley et al., 2002b; Ingham et al., 2013; McIntyre and Kilding, 2015; Wilkerson et al., 2004). When compared to a continuous warm-up of lower intensity, a priming protocol involving 5 x 10 s near-maximal sprints (50 s recovery) have been shown to enhance kayak 2 min TT performance by a small (ES: 0.2) but statistically significant margin (Bishop et al., 2003). Conversely the same protocol 5 min prior to a 3 km cycle TT had no effect on outcome, and was shown to attenuate performance if sprints were completed maximally (McIntyre and Kilding, 2015). Utilising a longer inter-repetition recovery duration (5 min), and rest period prior to the onset of exercise (15 min), maximal sprints (3 x 30 s) were shown to enhance the amplitude to which $\dot{V}O_2$ rose during peri-maximal-intensity cycle exercise by 11% (Wilkerson et al., 2004). Similarly, the use of a single high-intensity run (200 m), performed 20 min prior to an 800 m TT, provided a significantly faster time (1.2 s) compared to a control trial, which utilised 6 x 50 m 'strides', typical of traditional warm-up for a middle-distance runner (Ingham et al., 2013). Collectively these results demonstrate that a high-intensity bout of priming activity can positively influence $\dot{V}O_2$ kinetics and middle- and long-distance performance, providing the protocol does not lead to excessive fatigue caused by the interaction between exercise intensity and recovery duration.

The mechanisms which underpin an enhancement in $\dot{V}O_2$ kinetics and/or performance as a result of priming activity, are thought to relate to an improvement in the ability to deliver oxygen to active tissues (Murias et al., 2014) or activation of processes associated with oxidative metabolism (Jones et al., 2003a). It has also been proposed that prior high-intensity exercise necessitates an increase in firing and/or recruitment of higher threshold motor units, which are subsequently accessible at the onset of exercise (Jones et al., 2003a). This may allow a greater number of muscle fibres to share the load imposed by exercise and decrease the demand to recruit further motor units as exercise progresses. This hypothesis is supported by works which show increases in integrated EMG (iEMG) at the onset of exercise (Burnley et al., 2002a) and during the latter half of intense exercise (Tordi et al., 2003) following priming. Interestingly, Burnley and colleagues (2002a) observed the improvement in $\dot{V}O_2$ kinetics during the primary component closely matched the increase in iEMG which was observed. This evidence indicates that other forms of high-intensity exercise, such as a LCA, which is capable of activating a large pool of motor units (Sale, 1987), may offer an alternative means of enhancing middle- and long-distance performance.

2.6.3 Post-Activation Potentiation

Mechanistically PAP is defined as an increase in a twitch response that follows a brief MVC caused by the phosphorylation of MLC (Houston et al., 1985; Vandervoort et al., 1983). Contemporary definitions of PAP encompass a range of different types of muscular contraction and tend to attribute acute improvements in a wide range of athletic performance tasks following a preconditioning stimulus to PAP (Maloney et al., 2014; Wilson et al., 2013). Moreover, evidence for MLC phosphorylation is somewhat weak in humans, therefore various authors have suggested that other mechanisms may also be responsible for a PAP response, including an increase in motor unit recruitment and changes in limb stiffness (Maloney et al., 2014; Tillin and Bishop, 2009). These mechanisms have been shown to facilitate a short-term improvement in neuromuscular performance that may also have utility for middle- and long-distance related outcomes.

The efficacy of a PAP inducing stimuli on performance in skills requiring power has been discussed in several recent reviews (Gouvea et al., 2013; Maloney et al., 2014; Seitz and Haff, 2016; Wilson et al., 2013). Ballistic exercise protocols (3-5 repetitions of DJ, weighted jumps and weightlifting derivatives) and heavy resistance exercise (> 85% 1RM or 3RM) have consistently been shown to enhance (2-5%) vertical jump, sprint performance (≤ 100 m), repeated sprint ability and change of direction speed following a recovery duration of 5-10 min recovery. The effect of a PAP protocol on middle- and long-distance related outcomes has received far less attention. Given the paucity of literature, an examination of the mechanisms that underpin a PAP response could provide clues as to whether a benefit could exist.

2.6.3.1 Phosphorylation of Myosin Light Chains

Although PAP can be elicited in both type I and type II fibres, athletes with a higher percentage of type II fibres, and therefore greater MLC, tend to experience higher levels of potentiation (Vandervoort et al., 1983). Studies that have demonstrated positive outcomes from a LCA on explosive performance tasks have typically used athletes from intermittent high-intensity sports and/or participants with a background in ST (Maloney et al., 2014; Seitz and Haff, 2016). Furthermore, there appears to be a clear link between strength status and the amplitude of a potentiation response (Chiu et al., 2003; Gourgoulis et al., 2003). This suggests that athletes who excel in endurance-based sports, who typically possess a high proportion of type I fibres (Costill et al., 1976b), might be expected to elicit a lower PAP response compared to strength-trained athletes. Despite this supposition, endurance-trained athletes are capable of eliciting a greater twitch potentiation response compared to untrained individuals following a MVC (Hamada et al., 2000). Endurance training has also been shown to enhance shortening velocity of type I fibres (Fitts and Holloszy, 1977; Schluter and Fitts, 1994), with a concomitant increase in MLC (Schluter and Fitts, 1994). This adaptation in the trained muscles of endurance-trained athletes has been attributed to an increased capacity for MLC phosphorylation, which therefore increases the potential of eliciting a PAP response (Hamada et al., 2000).

Following a peri-maximal voluntary contraction, fatigue and potentiation can coexist within a muscle (MacIntosh and Rassier, 2002), with the magnitude of both a consequence of the nature of the contraction and the characteristics of the individual. Due to a superior resistance to fatigue in endurance-trained athletes, potentiation effects have also been shown to prevail for longer during an intermittent fatiguing task, compared to power-trained athletes (Morana and Perrey, 2009). Potentially therefore, despite possessing a relatively low percentage of type II fibres (and thus MLC), middle- and long-distance athletes could have the capability to amplify a PAP response in trained muscles, which may also be sufficiently long-lasting to benefit performance. In addition, it is also recognised that a PAP state provides the largest benefits during dynamic activities requiring low frequency force outputs (Green and Jones, 1989; Vandenboom et al., 1993). These frequencies approximate the firing rates required to sustain repeated submaximal contractions (de Luca et al., 1996; Hamada et al., 2000), which implies PAP could potentially be used to augment middle- and long-distance performance.

2.6.3.2 Motor Unit Recruitment

A LCA such as an MVC or a series of explosive dynamic contractions, require the activation of high threshold motor units (Sale, 1987). During such contractions, high frequency electrical impulses provide the input required to release large quantities of neurotransmitter at the neuromuscular junction, thus ensuring the activation of large motor units. Additionally, during a conditioning activity where a muscle is stretched rapidly, such as a plyometric exercise, Ia afferent fibres respond via the muscle spindle apparatus by transmitting high frequency impulses to the spinal cord (Kakuda and Nagaoka, 1998). This elicits a stretch reflex response whereby for each parent Ia fibre, multiple synapses project action potentials to adjacent efferent α-motoneurons (Aagaard et al., 2002). This in turn elevates output from the motoneuron pool, which can be detected as the second response to an artificially evoked contraction on an EMG trace, known as a H-wave (Aagaard et al., 2002). It has been shown that an induced tetanic contraction is capable of acutely elevating the transmittance of excitation potentials via the Ia afferent at the spinal cord and reduces the threshold for activation in higher order motor units (Hirst et al., 1981; Lüscher et al., 1983). This potentially allows a greater level of force to be developed for the same electrical input during activities that have a high reliance on the stretch-shortening cycle. Moreover, an increase in H-wave amplitude has been observed following MVCs in the plantarflexors (Güllich and Schmidtbleicher, 1996; Trimble and Harp, 1998) and knee extensors (Folland et al., 2008b) during the 5-11 min period post-LCA. Although the evidence for enhanced motor unit recruitment following a LCA is mainly derived from studies in animal models or using artificial stimulation, it is possible that PAP could exert a beneficial effect during dynamic activities of various durations via this mechanism (Sale, 2004; Tillin and Bishop, 2009).

It is well-established that during sub-maximal exercise, both PAP and fatigue are present within the muscle, and consequently PAP is thought to provide a mechanism to counteract the effects of peripheral fatigue during prolonged exercise (Boullosa et al., 2011; Rassier and Macintosh, 2000). When this effect becomes depressed during the latter stages of exercise due to impaired excitation-contraction coupling, it has been postulated that an augmentation of the PAP response may enable force to be maintained for longer (Green and Jones, 1989; Rassier, 2000). Similarly, as middle- and long-distance events require relatively low motor unit firing frequencies, even a small enhancement in the force delivered by the motor units should improve performance (Sale, 2004). Moreover, for a given intensity of sub-maximal exercise, a state of potentiation, which provides a more accessible pool of motoneurons, should result in motor units decreasing their firing frequency, thus delaying the onset of fatigue (Hamada et al., 2000; Sale, 2004). A reduction in motor unit firing frequency has been shown during the early part of sustained isometric contractions without any compensatory activation of other motor units (de Luca et al., 1996). It was suggested that a PAP response may partly explain this finding (de Luca et al., 1996).

2.6.3.3 Stiffness

Stiffness refers to the ability of a body, limb or joint to resist the application of a force (Brughelli and Cronin, 2008). An increase in musculotendinous stiffness would theoretically reduce energy cost of exercise, as a stiffer structure enables muscles to achieve a quasi-isometric states more rapidly. This in turn influences both the magnitude and rate of shortening velocity in muscle fascicles reducing the amount of muscular work performed (Fletcher et al., 2013; Fletcher and MacIntosh, 2017). Improved musculotendinous stiffness also enables a greater contribution of mechanical work to be derived from storage and return of elastic strain energy in the Achilles tendon (Roberts et al., 1997). A relationship between musculotendinous stiffness and RE has previously been reported (Arampatzis et al., 2006; Dumke et al., 2010; Rogers et al., 2017), and increases in tendon stiffness following a period of HRT have been shown to correlate ($r^2 = 0.43$, p=0.02) with improvements in RE (Fletcher et al., 2010). Moreover, as running speed increases, tendon elastic strain energy provides a greater contribution to the work performed by the muscle-tendon unit at the ankle plantar-flexors (Lai et al., 2014), Therefore it is likely that for a well-trained middle-distance runner who operates at relatively high speeds, an enhancement in this quality would improve performance.

Higher stiffness is also related to greater concentric-dominant muscular capacity (Wilson et al., 1994), which may be relevant for sports such as cycling, cross-country skiing, and swimming. Indeed, higher levels of musculotendinous stiffness have been shown to correlate with cycling speed (Watsford et al., 2010), and double poling velocity in cross-country skiing (Lindinger et al., 2009), thus an acute improvement in this physiological attribute may provide a mechanism to enhance performance for middle- and long-distance athletes. It has also been suggested that an acute enhancement in limb stiffness may offer an additional explanation for the improvements observed in explosive activities following a LCA (Maloney et al., 2014).

Following a LCA used to induce PAP, both the muscular properties and the tensile mechanisms of a musculotendinous unit are likely to be affected (Gago et al., 2014). A previous review concluded that there was moderate evidence for decreased Achilles tendon stiffness (measured via ultrasound) after MVC, however activities involving a stretch-shortening cycle, such as running and hopping, have minimal effect (Obst et al., 2013). A subsequent investigation observed a PAP response without alteration in tendon stiffness following a single 6 s MVC (Gago et al., 2014), demonstrating fatigue may be an important factor modulating short-term changes in stiffness. It seems therefore that the direction and extent of alterations in stiffness following a LCA are influenced by the mode and dosage of exercise employed (Obst et al., 2013). Tendons in particular appear to be more resistant to fatigue during conditioning activities that utilise the stretch-shortening cycle. This has implications when examining the efficacy of such strategies upon middle- and long-distance disciplines that rely heavily upon musculotendinous stiffness.

Assessing changes in tendon structures provides one perspective on stiffness, however changes in vertical or limb stiffness may be the consequence of morphological alterations in other tissues or segments. Leg stiffness and ground contact time during a drop jump task performed on a sledge was shown to be positively affected following a set of back squats at 93% of 1RM in elite rugby players (Comyns et al., 2007). Similarly, improvements in vertical stiffness during a CMJ following three back squat repetitions at 90% 1RM in female volleyball players have been observed (Moir et al., 2011). In contrast to the aforementioned studies, these results indicate that a LCA may provide a suitable stimulus to acutely enhance leg and vertical stiffness during activities that require the stretch-shortening cycle, such as distance running. Moreover, leg stiffness has been shown to decrease with fatigue in runners (Hayes and Caplan, 2014), therefore an increase in stiffness at the onset of exercise may offset this reduction.

2.6.4 Experimental Evidence

The foregoing discussion suggests that the inclusion of a LCA within the warm-up routine of middle- and long-distance athletes could augment subsequent performance outcomes. Only four studies have attempted to examine this conjecture experimentally (Table 2.4), yielding mixed results. Two studies have investigated the effect of heavy resistance exercise on middle- (Feros et al., 2012) and long-distance (Silva et al., 2014) performance. Silva and colleagues (2014) found an improvement (-6.1%, p=0.02, ES=0.38) in 20 km TT performance in well-trained cyclists following 4 sets of 5RM on a leg press. The authors attributed the improvement to an increase (5.8%) in mean power during the first 2 km of the test, as little difference was observed across other split times. Similarly, Feros and co-workers (2012) utilised 5 x 5 s isometric contractions on a rowing ergometer to successfully enhance the first 500 m of a 1 km TT performance in elite international rowers (-1.9%, p=0.009, ES=0.62), however an improvement in 1 km TT performance was not noted compared to the control trial. Both studies found no change in perceived exertion between trials, which is thought to regulate effort during endurance performance (St Clair Gibson et al., 2006). This suggests that potentiation in the neuromuscular system allowed a greater amount of power to be developed during the first few minutes of exercise for the same level of effort. It therefore appears that a LCA could be beneficial for the early stages of a middle- or long-distance TT effort, however it is unclear whether potentiating starting speed facilitates an improvement in overall performance.

Table 2.4. Summary of studies which have investigated the acute effects of a loaded conditioning activity upon variables related to performance in middle- and long-distance athletes.

BL = blood lactate, BM = body mass, CC = conditioning contractions, ES = effect size, PP = peak power, NSS = no statistical significance ($p<0.05$), RE = running economy, RM = repetition maximum, rpm = revolutions per minute, RT = resistance training, TT = time trial

Authors	Participants	Sport	Training status	Potentiation protocol	Recovery	Performance protocol	Main findings compared to control condition
Barnes et al.	11 male	Distance running	Well-trained ($\dot{V}O_{2max}$ 62.1 ±5.9 $mL.kg^{-1}.min^{-1}$, 5 km 16.0 ±1.0 min)	6 x 10 s weighted vest (20% BM) sprints ~1500 m pace	10 min	5 min run @14 $km.h^{-1}$, incremental test to exhaustion	RE: -6.0% (ES=1.40), peak running speed 2.9% (ES=0.35), %$\dot{V}O_{2max}$ -7.2% (ES=0.68)
Chorley and Lamb	10 male	Cycling	Highly-trained ($\dot{V}O_{2max}$ 65.3 ±5.6 $mL.kg^{-1}.min^{-1}$, 8.2 ±6.0 years cycling),	3 x 10 s @70% PP, 60 rpm (30 s recovery)	5 min	4 km Wattbike TT	TT: -0.5% (ES=0.26), mean power (ES=0.24), mean Force (ES=0.21) all NSS. 0-1.5 km $\dot{V}O_2$: 6.8% ($p<0.05$, ES=0.97) 4 km TT $\dot{V}O_2$: 2.4% ($p<0.05$, ES=0.28)
Feros et al.	9 male, 1 female	Rowing	Elite ($\dot{V}O_{2max}$ 68.7 ±3.1 $mL.kg^{-1}.min^{-1}$, >5 years RT history)	5 x 5 s (15 s recovery) isometric CC on rowing ergometer	4 min	1 km rowing ergometer TT	0-500 m TT split: -1.9% ($p=0.009$, ES=0.62) 0-500 m TT power: 6.6% ($p=0.007$, ES=0.64). 1 km TT (ES=0.21), mean power (ES=0.26) both NSS
Silva et al.	11 male	Cycling	Well-trained ($\dot{V}O_{2peak}$ 56.7 ±6.7 $mL.kg^{-1}.min^{-1}$, 2-10 years running)	4 x 5RM leg press	10 min	20 km static cycle TT	TT: -6.1% ($p=0.02$, ES=0.38). 0-2 km mean power: 5.8% ($p=0.06$, ES=0.22) 2-18 km (2.7%) and 18-20 km (0.8%) both NSS. Mean power (ES=0.11), $\dot{V}O_2$ (ES=0.19), BL (ES=0.13) all NSS

Barnes et al. (2015) used six sprints wearing a weighted vest (20% body mass) to achieve beneficial effects to RE (-6.0%, ES=1.40) and peak running speed (2.9%, ES=0.35) in a group of well-trained distance runners. The authors observed a very high correlation (r=-0.88) between changes in peak speed and changes in leg stiffness. Evidence for individual responses to the LCA were also present. The acute improvements achieved in RE in this study are of a similar magnitude to those achieved following a 8-14 week explosive ST intervention (Berryman et al., 2010; Millet et al., 2002; Paavolainen et al., 1999a), and are likely to be sufficient to provide a performance benefit (Hoogkamer et al., 2016). Recently, Chorley and Lamb (2017) used a similar protocol in a group of highly-trained cyclists. Prior to a 4 km TT, participants performed three 10 s loaded sprints (70% peak power output) at a low cadence (60 rpm). The results showed a small (ES=0.2-0.3) and non-significant ($p>0.05$) change in completion times, mean power output and mean peak force, however the authors suggested that the improvements were meaningful in the context of the SWC value (Chorley and Lamb, 2017). A statistically significant increase in $\dot{V}O_2$ during the first 1.5 km (6.8%, ES=0.97) perhaps indicates an enhancement in rate adjustment of the oxidative system, or again, a potentiation effect benefited the initial stages of exercise.

2.6.5 Implications and Modulating factors

A PAP response is modulated by a number of variables that each require consideration to ensure a performance benefit is optimised. These factors have been reviewed extensively for short-duration athletic performance (Maloney et al., 2014; Seitz and Haff, 2016), however recommendations should be examined for appropriateness in the context of middle- and long-distance performance. Based upon the available evidence, Figure 2.8 provides a suggested warm-up protocol that middle- and long-distance athletes could adopt to enhance their performance. There is convincing evidence that following an initial low intensity warm-up, pre-performance preparation should include a higher intensity priming component (e.g. 3-6 min at 60-85% peak power output) to facilitate the $\dot{V}O_2$ kinetic response during the early stages of exercise (Bailey et al., 2009; Gurd et al., 2006; Mattioni Maturana et al., 2017). Following a 5-10 min passive recovery from this aerobic phase of warm-up, a performance advantage is likely to be gained by including either near maximal intermittent sprints (4-6 x ~10 s) or a LCA designed to elicit a PAP response. Based upon the experimental evidence to date, it is likely that a PAP response will only be realised under a specific set of circumstances.

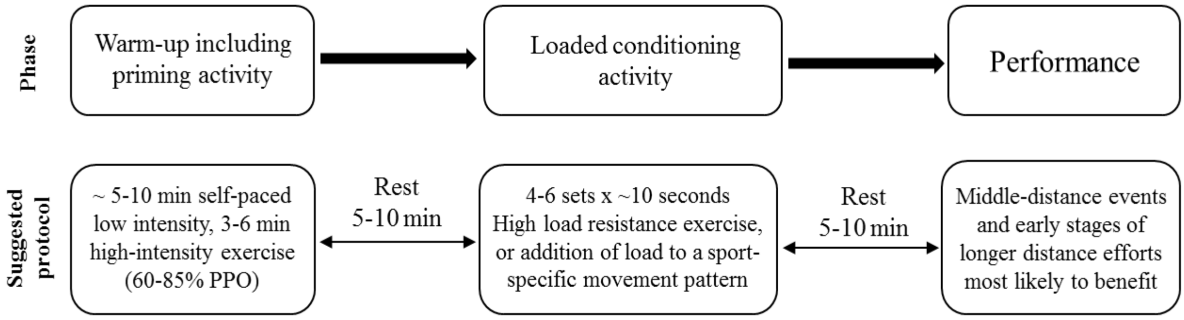


Figure 2.8. Suggested warm-up protocol for a middle- or long-distance athlete, including use of a conditioning activity to potentiate performance. PPO = peak power output

2.6.5.1 Participant Characteristics

As discussed, type II muscle fibres have a greater affinity for a PAP response (Hamada et al., 2000), thus endurance-trained individuals, who typically possess a low percentage of type II fibres (Costill et al., 1976b; Steinacker, 1993), are less likely to benefit from a LCA compared to strength-trained athletes. It is likely therefore, that middle-distance competitors, who possess a more even split of fibre phenotypes (Costill et al., 1976a) might benefit from a warm-up that includes a LCA more-so than a long-distance athlete. It is also possible that older endurance athletes have a lower capacity to generate a PAP response as age-related reductions in muscle mass have been attributed to smaller type II fibre size (Nilwik et al., 2013).

As expected, strength-trained athletes tend to exhibit a larger PAP response (ES=0.53) than athletes with no ST experience (ES=0.07) irrespective of strength-level (Seitz and Haff, 2016). It has been reported that well-trained rowers and swimmers regularly utilise ST as part of their training routine (Aspenes and Karlsen, 2012; Lawton et al., 2011), and highly-trained distance runners include ST modalities more so than recreational runners (Esteve-Lanao et al., 2007; Voight et al., 2011). The well-trained runners, cyclists and rowers in the studies that observed an improvement in performance following a LCA had ST experience (Barnes et al., 2015; Feros et al., 2012; Silva et al., 2014), therefore it appears that possessing a background in ST may be important to ensure a LCA is beneficial. Furthermore, highly-trained endurance athletes are capable of eliciting an amplified PAP response, the extent of which appears closely related to the training status of the limb exposed to the LCA (Hamada et al., 2000; Morana and Perrey, 2009). It seems that training status *per se*, may therefore be as important as ST experience when considering the type of athlete who may benefit from a LCA. This could be attributed to an athletes skill level on a LCA, as better inter-muscular co-ordination on a task is likely to enable higher threshold motor units to be activated (Bernardi et al., 1996). In this regard, it may therefore be possible that a learning-effect exists, whereby middle- and long-distance athletes with less ST experience are able to benefit from a LCA following a number of exposures to a PAP-type protocol. Further investigation is required to confirm this conjecture.

2.6.5.2 Loaded Conditioning Activity

A recent meta-analysis indicated that plyometric- and (high-load) resistance-based exercise provide a similar PAP response (ES: 0.41 and 0.47 respectively), whereas moderate load exercises and isometric contractions produce a negligible effect (ES: <0.2) on tasks requiring short bursts of explosive power (Seitz and Haff, 2016). Results from the studies on middle- and long-distance performance (Table 2.4) corroborate this finding. Silva et al. (2014) observed an improvement (-6.1%, ES: 0.38) in 20 km cycling performance following 5RM leg pressing, and 1 km rowing performance was unaltered by a series of 5 x 5 s isometric contractions (Feros et al., 2012). No studies to date have attempted to use a traditional plyometric exercise to elicit a PAP response in endurance athletes. However Barnes and colleagues (2015) added load (20% body mass) to sprints (6 x 10 s) and achieved improvements in RE (-6.0%, ES: 1.40), peak running speed (2.9%, ES: 0.35) and %$\dot{V}O_{2max}$ (-7.2%, ES=0.68).

When attempting to exploit PAP to enhance performance, a sufficiently high-intensity LCA is required to induce potentiation, however this also produces a high-level of fatigue. A recent review provides evidence for impairments in endurance-related performance for up to 72 h following a single bout of resistance training (Doma et al., 2017). Obviously performing multiple exercises and/or high load volumes will generate a level of neuromuscular fatigue that is likely to adversely affect a bout of endurance exercise performed immediately after. However, several studies have observed high levels of fatigue generated from a prescription that is not excessively different to the studies reviewed (Doma and Deakin, 2013; Michaut et al., 2000; Stock et al., 2010). For example, Michaut and colleagues (2000) found reduced twitch activation from 2 min to 48 h following 5 sets of 10 eccentric contractions. Although it appears that multiple sets and a low number of repetitions of a LCA optimise a PAP response, the effect is mediated by both strength-level and exercise intensity (Seitz and Haff, 2016; Wilson et al., 2013). It is likely that athletes who lack ST experience will develop higher levels of fatigue compared to those who are familiar with LCA-type exercises, however the enhanced fatigue resistance of endurance-trained athletes means they display similar recovery profiles to strength-trained individuals (Morana and Perrey, 2009). Thus a relatively low volume (≤ 6 sets x 3-5 repetitions or ~10 s) of sub-maximal contractions is most likely to yield a beneficial response (Maloney et al., 2014; Seitz and Haff, 2016). Further research is warranted to ratify this suggestion.

A limitation of many PAP inducing techniques is the requirement for heavy and expensive equipment, which cannot be easily accessed in a field-based setting or prior to competition. Having the option to elicit a PAP response without the need for specialist equipment or facilities would be of considerable practical benefit for endurance athletes and their coaches. Thus, there is appeal in protocols that add additional load to sport-specific movement patterns using portable inexpensive strategies (Barnes et al., 2015; Feros et al., 2012). Plyometric-based exercise may also provide an effective means of achieving a PAP outcome, however this is yet to be determined in middle- and long-distance athletes.

2.6.5.3 Recovery Following Loaded Conditioning Activity

The recovery time between a LCA and the outcome activity is crucial to ensuring fatigue has dissipated sufficiently yet a state of potentiation in the neuromuscular system remains (Wilson et al., 2013). This presents a dilemma, which several studies have attempted to resolve by investigating the time course of the decay in PAP and fatigue to identify the optimal window of time where the net gain from potentiation is highest (Gilbert and Lees, 2005; Kilduff et al., 2007; Kilduff et al., 2008). Passive rest intervals of between 5-12 min after heavy resistance activities (Gouvea et al., 2013; Seitz and Haff, 2016; Wilson et al., 2013) and 1-6 min following a ballistic exercise (Maloney et al., 2014) have been suggested to enhance a short duration task. However, the temporal profile of a PAP response is also modulated by training status. Although weaker individuals appear to require longer (>8 min) recovery periods to realise a PAP response, aerobic fitness is related to an ability to recover from high-intensity exercise (Tomlin and Wenger, 2001). Benefits to the early part of middle-distance efforts have been shown using a recovery duration of 4-5 min in endurance-trained athletes (Chorley and Lamb, 2017; Feros et al., 2012), however overall performance did not benefit from this scenario, perhaps suggesting some residual fatigue caused by the LCA was still present. Depending upon the activity utilised to induce PAP, it is therefore likely that a recovery period of between 5-10 min should be adopted to maximise the likelihood of middle- and long-distance performance being enhanced.

2.6.5.4 Outcome Activity

A PAP response is transient and appears to provide negligible effects on power performance beyond approximately 12 min post-LCA (Gouvea et al., 2013; Wilson et al., 2013), but prevails for longer in endurance-trained athletes compared to power-trained individuals (Morana and Perrey, 2009; Pääsuke et al., 2007). This indicates that if long-distance athletes benefit from a PAP response, it would be likely to affect only the initial part of a performance. It may also be the case that middle-distance performances lasting <3 min might gain more benefit compared to longer distance efforts. Studies that have used high-intensity sprinting as part of a warm-up lend support to this notion as improvements in swimming, running and kayak performance lasting 1-2 min have been demonstrated (Bishop et al., 2003; Hancock et al., 2015; Ingham et al., 2013).

Studies to date have tended to focus upon measuring TT performance (Chorley and Lamb, 2017; Feros et al., 2012; Silva et al., 2014), which provides a high level of ecological validity. Assessment of movement economy and efficiency, which have been shown to benefit from chronic exposure to ST (Beattie et al., 2014; Berryman et al., 2017) are also likely to benefit from acute potentiation of the neuromuscular system. Preliminary evidence is contradictory in this regard as Barnes and colleagues (2015) observed large improvements in RE following a series of weighted vest sprints, whereas Silva et al. (2014) found no change in $\dot{V}O_2$ during a 20 km cycle TT. The discrepancy is likely due to the intensities used to assess economy in these two papers, therefore future work should use a common relative intensity (below LT) in participants.

2.7 Strength Training in Adolescent Athletes

Adolescence refers to the period of life between childhood and adulthood, typically considered to be between age 12-18 years in girls and 14-18 years in boys (Lloyd et al., 2014). The long-term health and fitness benefits of participating in a well-rounded programme of physical activities and sports during this period, which promotes physical literacy and develops a breadth of physical qualities, is well recognised (Lloyd et al., 2015; Roetert and Jefferies, 2014). It is argued that a systematic approach to the development of young athletes is grounded in a progressive and well-managed programme of ST, which enables aspiring young athletes to cope with the rigours of sports training and reach their potential (Faigenbaum, 2017; Faigenbaum et al., 2016; Lloyd et al., 2014). ST techniques develop a broad range of physical capacities such as agility, speed, muscular strength, balance, co-ordination, and motor control, which underpin performance across numerous sports and everyday living tasks (Lloyd and Oliver, 2012). Moreover, ST activities which develop neuromuscular function are likely to offset the risk of injury in youth athletes (DiFiori et al., 2014; Myer et al., 2011), which may reduce drop-out rates and facilitate the transition of talented young performers to an elite level (Fort-Vanmeerhaeghe et al., 2016; Myer et al., 2016). Several leading professional organisations and authorities in the area of paediatric exercise science and sports medicine have published statements advocating the inclusion of age- and individual-appropriate ST activities for young athletes (Behm et al., 2008; Bergeron et al., 2015; Faigenbaum et al., 2016; Granacher et al., 2016; Lesinski et al., 2016; Lloyd et al., 2016; Lloyd et al., 2014; McCambridge and Stricker, 2008; Smith et al., 2014).

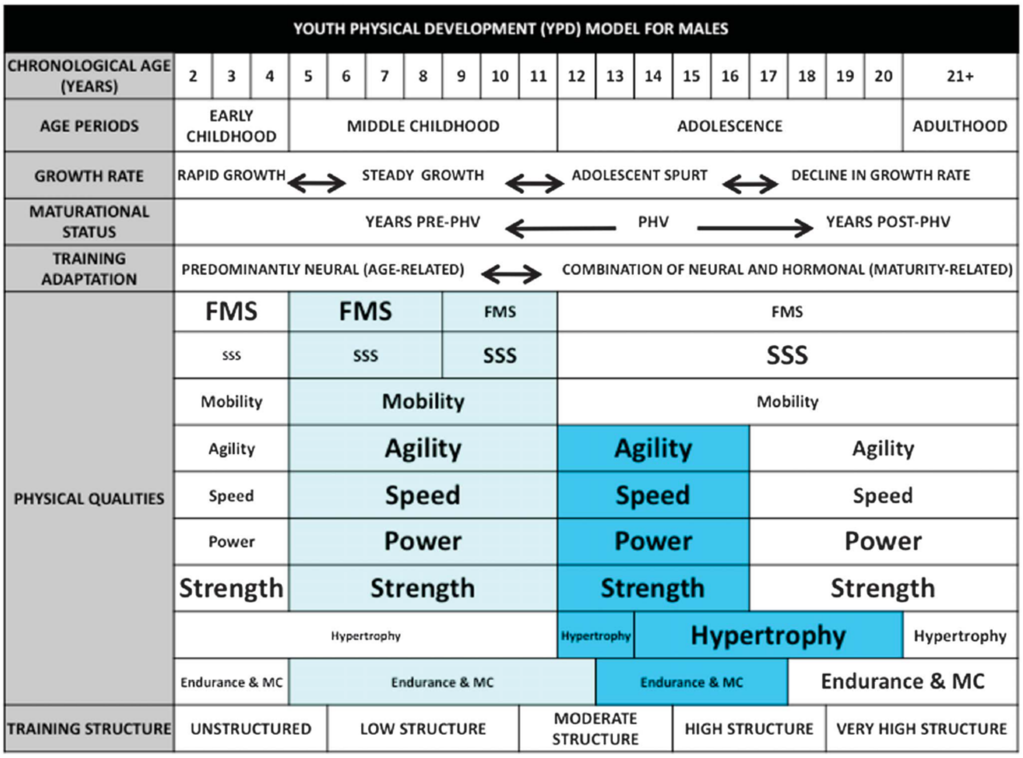
2.5.1 Early-Sport Specialisation and Long-Term Athlete Development

Childhood and adolescence represents a crucial period of development in young athletes where a significant alteration in hormonal status causes rapid physical growth, development of sexual characteristics, and attainment of reproductive capacity (Malina, 1994). Contemporary models of long-term athlete development suggest adolescents should avoid training routines that focus on intensive training in a single sport (for >8 months per year), or a total weekly training volume which exceeds the athletes age in years, until late-adolescence (Lloyd et al., 2016; Lloyd and Oliver, 2012; Myer et al., 2016). Whilst some degree of sport-specialisation is necessary during adolescence to reach elite status, the timing of single sport-specialisation is more controversial. Evidence across a range of sports shows elite senior athletes tend to specialise at a later age, and participate in a diverse range of sports during their childhood (Côté et al., 2009; Moesch et al., 2011). Young athletes who adopt an early-diversification, late-specialisation approach to their development have fewer injuries, are at less risk of overtraining, and play sports longer than those who specialise in one sport before puberty (Brenner, 2016; DiFiori et al., 2014).

Figure 2.9 shows the youth athlete development models for males (a) and females (b), which suggests that training during childhood and adolescence should prioritise the development of rudimentary motor skills and muscular strength (Lloyd et al., 2016; Lloyd and Oliver, 2012). The emphasis on ST activities throughout an athlete's development is thought to maximise adaptations to neuromuscular coordination, motor unit recruitment and motor control, during a period when neuroplasticity is high (Blimkie, 1992; Myer et al., 2013). The model suggests that a wide range of physical activities and training modalities should be utilised through a child's development, however neuromuscular training that aims to enhance strength qualities and motor skills should be prioritised (Lloyd and Oliver, 2012). Improvements in muscular strength and motor control during this period have also been shown to improve physical performance (Behringer et al., 2011; Lesinski et al., 2016) and lower the risk of sustaining an injury (Myer et al., 2011; Steib et al., 2017; Valovich McLeod et al., 2011). It is recommended that endurance training (and metabolic conditioning) is not emphasised, relative to other biomotor abilities, until late-adolescence (Lloyd and Oliver, 2012), as typically this type of training is associated with high volumes of work, which may lead to overtraining (Baxter-Jones and Helms, 1996; Matos and Winsley, 2007). Moreover, pre-pubertal children have tended to show smaller changes (<10%) in aerobic measures following endurance training interventions compared to post-pubertal adolescents and adults (Matos and Winsley, 2007; McNarry and Jones, 2014). A recent study also showed that pre-pubertal boys (10.5 years) were metabolically comparable to well-trained endurance athletes and experienced less fatigue during high-intensity exercise compared to untrained adults (Birat et al., 2018). It was suggested that pre-pubertal children avoid specific training to develop aerobic metabolic qualities and shift priority during post-pubertal years once movement technique and mechanical efficiency have been developed (Birat et al., 2018). For the young distance runner who chooses to specialise in the sport during late-adolescence, it would therefore be interesting to identify whether ST offers a means of improving the performance-related factors that have been investigated so extensively in adult distance runners.

Recommendations associated with timing of single sport-specialisation and long-term athlete development were therefore applied to the present thesis, by ensuring that only post-pubertal participants ≥ 15 years old were recruited. Due to the risks associated with early-specialisation, it was considered that adolescent athletes younger than this age should not have specialised in a single-sport such as distance running, but should be participating in a number of other sports and physical activities. Participation in other sports would also be an important confounding factor that may potentially influence results of studies, therefore this inclusion criteria reduces this possibility and permits the participants to be defined as middle- and long-distance runners. It is also likely that post-pubertal adolescents are more likely to respond to endurance training in a similar manner to that of adult performers compared to pre-pubertal or circa-pubertal athletes (McNarry and Jones, 2014). Therefore the chronic impact of additional ST exercise can be evaluated in a more valid manner.

(a)



(b)

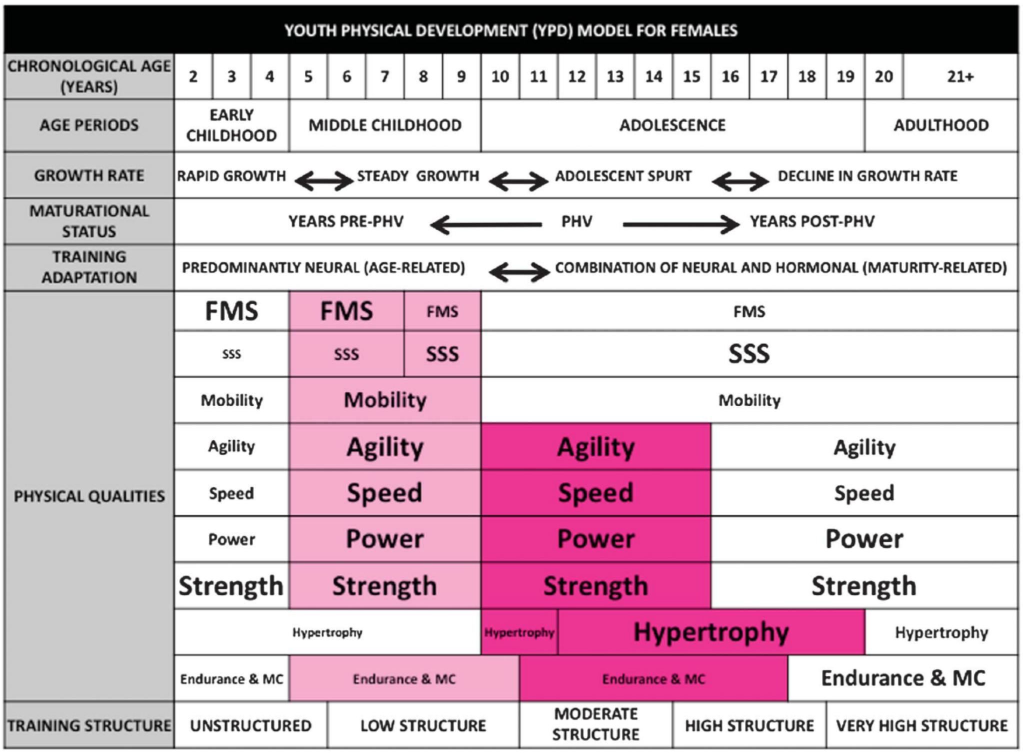


Figure 2.9a and 2.9b. The youth physical development model for males (a) and females (b) (Lloyd and Oliver, 2012). The size of the font reflects relative importance. Intensity of colour in the boxes refers to pre-adolsecent periods of devlopment (lighter) and adolescent periods of adaptation (darker). FMS = fundamental movement skills; MC = metabolic conditioning; PHV = peak height velocity; SSS = sport-specific skills.

2.7.2 Effects of Strength Training on Performance-Related Outcomes

A plethora of literature exists that demonstrates ST activities are a safe and effective way of enhancing proxy measures of athletic performance in children and adolescents of both sexes (Behringer et al., 2011; Harries et al., 2012; Lesinski et al., 2016; Lloyd et al., 2014). Specifically, in post-pubertal adolescents, compared to sport-only training, various forms of ST augment improvements in: muscular strength, explosive power, muscular endurance, sprint speed, agility test time, tennis serve velocity, kicking velocity, throwing velocity, and general motor skills (Behringer et al., 2011; Behringer et al., 2013; Behringer et al., 2010; Granacher et al., 2016; Harries et al., 2012; Legerlotz et al., 2016; Lesinski et al., 2016; Rumpf et al., 2012).

The safety of RT in young athletes has previously been questioned with concerns centred around epiphyseal plate injury and growth abnormalities the most commonly cited (Benton, 1982; Gumbs et al., 1982; Legwold and Kummant, 1982). However, any isolated observations associated with damage to growth cartilage appear to be related to poor lifting technique or inappropriate training volumes. Providing training is supervised and prescribed by a qualified practitioner, the current consensus in the field indicates that ST is not inherently harmful and does not pose a risk to epiphyseal plates or normal growth (Lloyd et al., 2014; Milone et al., 2013; Myers et al., 2017). Indeed, prospective investigations that have included appropriate levels of supervision and coaching have demonstrated no increased incidence of physeal-related injury (Ramsay et al., 1990) and overall low injury rates (Lillegard et al., 1997), even for programmes involving regular HRT (Faigenbaum et al., 2003).

Research investigating the impact of ST techniques on performance-related measures in young athletes has tended to use participants from field-based sports, martial arts, court sports, aquatic sports, gymnastics and strength-based sports (Granacher et al., 2016; Legerlotz et al., 2016; Lesinski et al., 2016; Rumpf et al., 2012). As part of the systematic review (Section 2.5) process, two studies were identified that used middle- or long-distance running participants under the age of 18 years. Mikkola et al. (2007) took a group of trained male and female distance runners (17.3 years, $\dot{V}O_{2max}$: 62.5 $mL \cdot kg^{-1} \cdot min^{-1}$) and following eight weeks of HRT and EST observed improvements in anaerobic capabilities (sMART and 30 m sprint). The study by Bluett and associates (2015) did not meet the inclusion criteria for the review, however ten weeks of concurrent aerobic and ST provided no strength advantage in 10-13 year old competitive runners compared to running only. The authors speculated that excessive fatigue resulting from the concurrent training regimen may have compromised both strength and endurance adaptations (Bluett et al., 2015). Interestingly, the blunting of strength adaptation which is often observed in adult performers when both strength- and endurance-training are included in the same training session (Wilson et al., 2012b) appears not to occur in children (Marta et al., 2013) and adolescents (Santos et al., 2011; Santos et al., 2012). As the interference phenomeon is mediated by training volume and recovery from sessions (Baar, 2006), it seems likely that the volumes of each training modality included in the aforementioned studies were insufficient to negatively impact upon strength-related adaptation. Indeed, in elite youth football players (17.3 years) who utilise higher workloads compared to younger performers, small but clinically meaningful differences were noted following different sequencing of strength- and sport specific endurance-training over five weeks, in favour of a strength-training first order (Enright et al., 2015).

2.7.2.1 Prescription of Strength Training for Adolescent Athletes

Recent reviews and meta-analytical studies examining the effects of ST on youth populations have provided recommendations regarding the most appropriate prescription of ST activities (Behringer et al., 2010; Granacher et al., 2016; Lesinski et al., 2016; Lloyd et al., 2014; Zwolski et al., 2017). It is important to highlight that evidenced-based guidelines should be adapted to the specific needs of individual athletes, which account for differences in ability, goals and movement competency. Pre-pubertal years (or the initial weeks for those with low RT skill competency) should be spent developing sound technique across a broad range of ST skills (1-2 sets x 8-15 repetitions at 30-60% 1RM, 1 min inter-set recovery), which can subsequently be loaded (2-4 sets x 6-12 repetitions at ≤ 80% 1RM, 2-3 min inter-set recovery) on 2-3 occasions per week (Behm et al., 2008; Faigenbaum et al., 2016; Lloyd et al., 2014). Dose-response relationships for key RT variables in post-pubertal youth athletes suggest that training intensity is the primary moderator of strength- and performance-related improvement (Behringer et al., 2011; Lesinski et al., 2016). Therefore, assuming skill competency is sufficiently high, RT programmes that utilise a low repetition range (6-8 repetitions per set) and heavier loads (80-89% 1RM) with a 3-4 min rest between sets are most effective (Faigenbaum et al., 2016; Lesinski et al., 2016). Free weights (barbells and dumbbells), which permit multi-planar movement, demand higher levels of balance, stability and motor control, thus have a greater transfer across to athletic performance tasks and should be the equipment of choice (Granacher et al., 2016; Lloyd et al., 2014). Other loading strategies have also been used successfully as part of RT programmes to elicit strength-related adaptation, including bodyweight, resistance machines, elastic resistance bands and medicine balls (Lloyd et al., 2014). These modalities are particularly suitable for those with low strength levels and/or RT skill competency.

The optimal approach to athlete development and to maximise performance-related outcomes involves a multi-modal approach to ST (Behm et al., 2008; Granacher et al., 2016). RT exercise should therefore be included alongside fundamental movement skills training, sports-specific training (e.g. SpT and running drills), PT, balance exercises and core stability training to provide a well-rounded approach to the development of neuromuscular-related qualities (Granacher et al., 2016; Lloyd et al., 2016; Steib et al., 2017). It is recommended that PT should commence with low-intensity bilateral exercises (e.g. low box/mini hurdle jumps), which focus on achieving proper landing technique and progress gradually in terms of volume (total foot contacts), intensity (eccentric demand) and skill complexity (limb support) (Behm et al., 2008; Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b). Total foot contacts for a session should start around 50 (1 set x 6-10 repetitions per exercise, 1-2 min inter-set recovery) and may progress up to 150 contacts (with an inter-set recovery of 2-3 min) for a youth athlete, depending upon biological age, skill level and intensity of the exercises (Lloyd et al., 2011). Alongside improvements of strength-related qualities, 'neuromuscular training' encompasses development of capacities associated with dynamic stability, movement co-ordination, speed and agility, and muscular endurance, which should also form part of the non-sport-specific training performed routinely by adolescent athletes (Fort-Vanmeerhaeghe et al., 2016; Myer et al., 2011; Steib et al., 2017). In conjuction with the ST principles associated with an improvement in distance running performance (Sections 2.5.4.10-2.5.4.12), these recommendations should be applied to the ST prescription of adolescent distance runners as part of a training intervention.

2.7.3 Effects of Strength Training on Endurance-Related Measures

A number of intervention studies that have investigated the effect of ST on adolescent athletes have included a measure related to endurance performance in their battery of tests (Bluett et al., 2015; Ferrete et al., 2014; Gorostiaga et al., 1999; Klusemann et al., 2012; Makhlouf et al., 2016; Mikkola et al., 2007; Potdevin et al., 2011; Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b; Ramírez-Campillo et al., 2015c; Ramírez-Campillo et al., 2014; Wong et al., 2010). In post-pubertal distance runners, Mikkola and colleagues (2007) noted a small but significant difference in RE at 14 $km \cdot h^{-1}$ (2.7%, ES=0.32, $p<0.05$) compared to a running-only group, and improvements in BL at 12 $km \cdot h^{-1}$ (12%, $p<0.05$) and 14 $km \cdot h^{-1}$ (11%, $p<0.05$) were also detected. However, in a younger cohort of distance runners, Bluett et al. (2015) observed no change in 3 km TT performance.

Other investigations that have studied young athletes from other sports specialisms have tended to use a combination of ST modalities. The inclusion of twice weekly onfield RT and ERT in the pre-season training (12 weeks) of under-14 year old male soccer players provided a moderate improvement (ES=0.94, 19.5%) in Yo-Yo intermittent endurance run performance and a small enhancement (ES=0.44, 5.1%) in RE, compared to soccer-only training (Wong et al., 2010). It should be noted however, that the CG possessed significantly lower $\dot{V}O_{2max}$ and Yo-Yo scores at baseline compared to the experimental group. Using the identical ST intervention as Wong et al. (2010), a similar finding was observed for Yo-Yo test performance in another group of male soccer players (13.7 years) who included concurrent strength- and endurance-training within the same session or on separate days (Makhlouf et al., 2016). Large improvements were found for a group who utilised the endurance-strength session structure (79%), strength-endurance session order (59%), and alternate day format (55%), which were all superior to the change seen in a CG (42%). Ferrete and colleagues (2014) also found large (50%, ES: 1.39) improvements in Yo-Yo test distance after ST

(HRT/ERT/SpT) was added to soccer training for 26 weeks in pre-pubertal players (8-9 years old). Conversely, Gorostiaga and co-authors (2004) failed to find any change in BL concentration and HR during a three-stage submaximal discontinous running test in a group of post-pubertal (17.2 years) soccer players, following the addition of two explosive ST sessions (ERT/PT) to a weekly programme of soccer training for 11 weeks. The lack of effect may be because the physiological measures selected were insufficiently sensitive to detect a difference between groups. Small improvements compared to a CG were also noted for Yo-Yo test result in a group of male and female basketball players (14-15 years), who added bodyweight movement training (twice weekly) to their programme of training for six weeks (Klusemann et al., 2012). It is likely that the overload provided during this short intervention was insufficient to elicit the physiological adaptations required to enhance performance, which was also confirmed by the small-moderate changes observed in strength-related tests.

Investigations that have added PT sessions to normal sports training have generally found only a small impact on endurance-related field tests. Potdevin et al. (2011) studied the effect of adding two PT sessions per week to a group of 13-15 year old male and female swimmers for six weeks. The intervention produced a trivial (4.3%, ES: 0.15) but significant ($p<0.01$) improvement in 400 m front crawl time compared to a swimming-only CG. A series of studies by Ramirez-Campillo and colleagues (2014; 2015a; 2015b; 2015c) experimented with adding bi-weekly PT sessions in various volume and intensity combinations for 6-7 weeks periods in circa-pubertal and post-pubertal (10-16 years) male academy soccer players. In most scenarios the PT interventions produced small (ES: 0.26-0.41) improvements in Yo-Yo test distance (Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b; Ramírez-Campillo et al., 2015c) or 2.4 km TT performance (Ramírez-Campillo et al., 2014), however the changes observed were not significantly greater than a CG in each case. The only scenario that provided a significantly greater enhancement (15.3%, ES: 0.31) in Yo-Yo test performance, compared to a CG, utilised a PT regimen with progressively increasing volume (60 to 120 foot contacts) over a six week period (Ramírez-Campillo et al., 2015c). However, this finding is likely due to the very small change seen in the CG (2.7%, ES: 0.07), because similar volumes of PT were also utilised in the other studies and the standardised change was similar to the effect observed in previous investigations (Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b).

2.8 Summary of Literature Review and Perspective

Long-distance running performance is underpinned by several important physiological variables, which are identified in the classical model as $\dot{V}O_{2max}$, RE and fractional utilisation (Bassett and Howley, 2000). In the late 1990's, following a series of studies by Paavolainen and associates (1999a, 1999b, 1999c), anaerobic and neuromuscular factors were added to a deterministic model of performance, as it was recognised that these parameters underpin RE and are related to long-distance running performance. Performance in middle-distance running events is strongly influenced by aerobic parameters, however owing to the higher running speeds observed compared to long-distance races, anaerobic capabilities and neuromuscular factors are known to make a significant contribution. Other physiological measures have also been highlighted as important determinants of middle- and long-distance performance, including s$\dot{V}O_{2max}$, critical speed and $\dot{V}O_2$ kinetics.

Although $\dot{V}O_{2max}$ is widely recognised as the gold standard physiological measure in distance runners, it is apparent that all runners possess an upper limit of improvement in this parameter. Other physiological determinants display large inter-individual differences, even in groups of runners with similar performance characteristics. RE in particular is influenced by a number of intrinsic and extrinsic factors, including neural and musculotendinous related qualities, which can be improved with non-running training strategies, such as ST activities. Specifically, ST brings about increases in motor unit recruitment, firing frequency and musculotendinous stiffness, which are thought to optimise the length-tension and force-velocity relationships of active skeletal muscle, thus reducing metabolic cost (Fletcher and Macintosh, 2017).

There are a number of biomechanical variables that also appear to be important for maximising RE. In particular, energy cost of running is minimised with low horizontal braking forces, small vertical oscillation of the centre of mass and less extended leg positions at toe-off. Gait re-training studies have demonstrated success in increasing stride frequency and improving foot strike position relative to centre of mass, however the impact of these interventions on RE and performance is unclear. ST may offer a means of enhancing some important kinematic variables via improvements in the ability to attenuate forces at ground contact, thus reducing the range of motion the joints of the lower limb move through, which reduces the contribution of active muscle to propulsion.

Relating to the first aim of this thesis, a systematic review was undertaken to comprehensively explore the efficacy of ST on the physiological determinants of middle- and long-distance running performance. The 26 studies reviewed met the following criteria: used participants with >6 months running experience, applied a ST intervention (≥ 4 weeks) consisting of HRT, ERT or PT, included a running-only CG and measured one or more physiological parameter relating to performance. The research reviewed suggested that supplementing the training of a distance runner with ST is likely to provide improvements to RE, TT performance and anaerobic parameters such as maximal sprint speed. Improvements in RE in the absence of changes in $\dot{V}O_{2max}$, BL and body composition parameters suggests that the underlying mechanisms predominantly relate to alterations in intra-muscular co-ordination and increases in tendon stiffness that contribute to optimising force-length-velocity properties of muscle. Nevertheless, it is clear that the inclusion of ST does not adversely affect $\dot{V}O_{2max}$ or BL markers. The addition of 2 or 3 supervised ST sessions per week is likely to provide a sufficient stimulus to augment parameters within a 6-14 week period, and benefits are likely to be larger for interventions of a longer duration. A variety of ST modalities can be used to achieve similar outcomes assuming runners are of a non-strength trained status, however to maximise long-term adaptations, it is suggested that a periodised approach is adopted with HRT prioritised initially. Although changes in fat-free mass were not observed in the majority of studies, a targeted RT programme, which aims to increase muscle mass specifically around the proximal region of the lower limb may enhance biomechanical and physiological factors which positively influence RE.

Despite the abundance of literature in this area showing a likely benefit to performance across a wide range of competitive levels, little is known about the extent to which the distance running community are engaging in purposeful ST exercise. It was also noted that very few investigations have examined the effect of ST on specific populations of runners such as young competitors (Mikkola et al., 2007), therefore this thesis will attempt to address this dearth in literature.

A number of methodological issues are likely to have contributed towards the discrepancies in results and will be acknowledged in the studies conducted as part of this thesis. In particular, the measurement of RE should be quantified as an energy cost (rather than oxygen cost) and a variety of speeds assessed that are relative to the maximum steady state of each participant. Furthermore, when quantifying RE and $\dot{V}O_{2max}$, differences in body size should be accounted for by using scaling exponents which are appropriate for the cohort under investigation. Measurement error has previously not been quantified for RE expressed as energy cost and $\dot{V}O_{2max}$ in adolescent distance runners after values are scaled appropriately for body mass. The nature of the running training undertaken by participants and ST history potentially confounds the outcomes of studies in this area, therefore attempts should also be made to control these variables as much as possible.

Warm-ups are commonplace in the pre-performance routine of middle- and long-distance athletes with the majority of research focussing on the $\dot{V}O_2$ kinetic response to various priming protocols. Over a decade ago, authors speculated that a PAP response evoked by a LCA included within an endurance athlete’s warm-up routine would provide a benefit to performance (Hamada et al., 2000; Sale, 2004). This was based upon the argument that PAP has its greatest effect during activities that require motor units to fire at relatively low force frequencies. However, despite an abundance of literature investigating the acute effects of a LCA on subsequent ballistic performance tasks, only recently have studies emerged that have investigated the PAP phenomenon in middle- and long-distance athletes. Despite the limited number of studies that have been conducted in this area to date, the tentative conclusion is that well-trained middle- and long-distance athletes are likely to obtain some benefit, particularly during the early stages of a performance, by including a LCA in their warm-up routine.

It is recommended that middle- and long-distance athletes experiment with a warm-up protocol (Figure 2.8) that involves a 5-10 min self-paced warm-up at a low intensity (~60% maximum HR or 40-60% peak power output) followed 5-10 min later by a LCA. It is likely that a short bout of high-load resistance exercise (4-6 sets x 5RM), plyometric exercise (1-6 sets x 3-5 repetitions), or series of sprint efforts (4-6 sets x ~10 s with the addition of a light-moderate load) will elicit a PAP response, however this is yet to be fully determined experimentally in middle- and long-distance runners. A recovery of 5-10 min should be permitted following the LCA to ensure fatigue has dissipated sufficiently to realise a benefit to performance. A young group of high-performing middle-distance athletes represent an intriguing group to investigate, as it is likely they would possess a higher proportion of type II fibres compared to their more experienced senior counterparts (Wilson et al., 2012a).

It is well-established that ST is a safe and effective training modality for young athletes. Moreover, age-appropriate ST should form an integral part of a well-rounded approach to the long-term physical development of all young sports performers. Despite the importance of engaging in a thoughtful and supervised programme of ST during adolescence, there is virtually no research which has investigated the potential for ST to benefit distance running performance in this population. Findings from studies using young athletes from other sports suggest a biweekly multi-modal approach to ST for periods of $\geq$ 8 weeks provides moderate-large benefits to field-based measures of endurance performance, compared to sport-only training. The physiological limitations to middle- and long-distance running performance are similar in this age-group to those identified for adult distance runners. Therefore, it would be interesting to observe whether a strength-based exercise intervention provides an acute and chronic benefit to physiological parameters relating to performance in post-pubertal adolescent runners.

CHAPTER 3

METHOD

Commentary published from this chapter:

Blagrove, R. C., Howatson, G. and Hayes, P. R. (2018) Quantification of exercise intensity as energy expenditure: reliability and units of measurement. Comment on: Beck, O.N., Kipp, S., Byrnes, W.C., Kram, R. Viewpoint: Use aerobic energy expenditure instead of oxygen uptake to quantify exercise intensity and predict endurance performance. *Journal of Applied Physiology*, in press for July 2018.

3.1 Introduction

This chapter will provide a brief overview of how the aims of the thesis will be addressed and describe the protocols that will be used to measure key variables across the thesis. Specific methods relating to individual experiments will be outlined as part of Chapters corresponding to each research aim.

3.2 Overview of Thesis Method

The overriding objective of this thesis was to further our understanding surrounding the use of ST activities in competitive distance runners. This was achieved by investigating current practices and examining the acute and chronic efficacy of ST exercise on physiological determinants, with a focus on adolescent runners. Specifically, five aims were identified in Section 1.1 and a visual representation of the experimental studies is provided in Figure 3.1.

As part of a wider literature review, the research that has examined the effect of various ST modalities on the physiological determinants and performance of middle- and long-distance runners was reviewed systematically (Study 1; see Section 2.5). Despite the fairly large body of literature in this area, it is currently unknown what proportion of competitive distance runners actually include these activities in their training regimen. A survey, to capture a large cross-section of the distance running community was therefore designed, with the aim of describing the current S&C habits in this population of athletes and the characteristics of those who participate in various activities (Study 2; see Chapter 3). This information would potentially be valuable to ascertain the extent to which findings from scientific research are being applied to training practices, and to help inform future research in this area.

Middle- and long-distance running performance is primarily limited by physiological factors, many of which can be assessed with a high degree of validity in a laboratory-based setting. Prior to the interpretation of any physiological data that is collected before and after a training intervention, it is important to ascertain the within-participant variability in measurements for the specific population under investigation. An initial test-retest reliability study was therefore conducted to identify TE values for the dependent variables that were subsequently used in other studies (Study 3; see Chapter 4). These values could also be applied by other scientists and practitioners conducting testing on the specific population recruited for this project.

Although it appears that the addition of ST sessions benefits RE, TT performance and anaerobic factors in adult runners, few investigations have examined whether a similar response is observed in specific populations of runners such as young (Mikkola et al., 2007), female (Johnston et al., 1997; Vikmoen et al., 2016; Vikmoen et al., 2017), and masters age (Piacentini et al., 2013) competitors. Specialisation in the sport of distance running should occur during the late-adolescence years, and thereafter, training is likely to become more structured and performance outcome-orientated (Lloyd et al., 2016; Lloyd and Oliver, 2012). This period of a young runner's development is therefore crucial, with ST strongly encouraged for health and performance benefits (Faigenbaum, 2017; Granacher et al., 2016). The dearth in literature in this population compared to research on adult runners, pre-pubertal children, and adolescent performers from other sports, precludes accurate recommendations being drawn. The cornerstone study of this thesis therefore examined the effect of a ST intervention on the physiological determinants of performance in post-pubertal adolescent distance runners (Study 4; see Chapter 5).

Manipulation of pre-performance routines to gain subtle performance advantages is a highly topical area of research (Kilduff et al., 2013; Maloney et al., 2014; Seitz and Haff, 2016) and potentially of considerable interest to practitioners preparing runners for training and competition. The theoretical and evidence-based rationale for including strength-based exercise 5-10 min prior to a middle- or long distance performance was discussed as part of the Literature Review (see Section 2.6). Despite the absence of a large number of experimental studies in distance runners, there appears to be a performance benefit to including a LCA in a warm-up routine. A group of high-performing junior middle-distance runners are likely to possess the physiological characteristics that would enable a potentiation response to be realised during a running performance. The acute impact of a LCA on physiological determinants and TTE was therefore assessed experimentally in a group of post-pubertal male distance runners (Study 5; see Chapter 6).

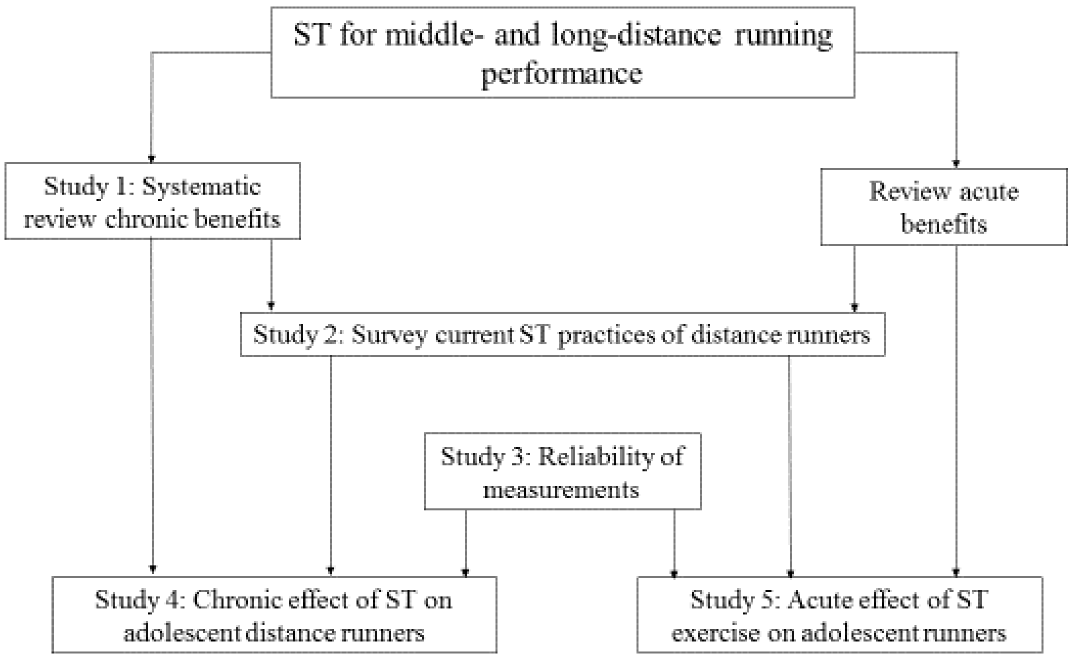


Figure 3.1. Schematic showing an overview of the research studies in this thesis. Arrows indicate information flow to inform study rationale, design and interpretation of results. ST = strength training.

3.3 Ethical Clearance

All four original research studies (studies 2, 3, 4 and 5) were conducted in accordance with the Helsinki declaration and received University level ethical approval (see Appendix A). All testing was conducted in the physiology laboratory, biomechanics laboratory and indoor Tennis centre at St Mary's University, Twickenham.

3.4 Participants

To be eligible to take part in any of the experimental studies (studies 3, 4 and 5), participants were required to meet the following inclusion criteria, which were identified through personal communication with the individual or a parent/guardian, and a pre-participation questionnaire (Appendix B):

- Aged between 15 - 18 years old (inclusive)
- Competed regularly at county, regional, national or international level in middle- (0.8 – 3 km) or long-distance (5 – 10 km and cross-country) running
- No formal ST experience
- Free from injury in the month preceding the study

Prior to commencing each study, participants were informed of the purpose, procedure and risks of the experiment and thereafter a parent/guardian (or if >18 years the participant themselves) provided signed consent to participate (see Appendix C). Participants also completed a Physical Activity Readiness Questionnaire (see Appendix D) to identify any medical conditions, musculoskeletal injuries or ailments that would preclude their participation in the research. The pre-participation questionnaire (Appendix B) also provided information on each participant's competitive history, strength training experience (if any), event specialism and current performance level. Participants performed each testing session in a hydrated state, at least 2 h post-prandial. Participants wore similar clothes and the same running trainers for each trial and were instructed to follow a similar pattern of exercise and diet in the 48 h prior to each trial, which included no strenuous exercise in the 24 h before trials.

3.5 Physiological Testing Protocols

Participants completed laboratory based testing sessions involving a discontinuous submaximal incremental running assessment to establish the response of BL, HR and pulmonary gas variables to increasing running speed, followed by a $\dot{V}O_{2max}$ test. A visual representation of the protocols is shown in Figure 3.2. Figure 3.3 shows photographs of the testing environment for two participants (with permission). Appendix E shows the data recording sheet used for the protocols described in this section.

3.5.1 Laboratory Environment

Trials were conducted at the same time of day (±1 h) for each participant to avoid any influence that diurnal variation may cause. All testing took place under standardised environmental conditions (temperature, 16-20 ºC; relative humidity, 29-54%; barometric pressure, 746-773 mmHg) in the same laboratory.

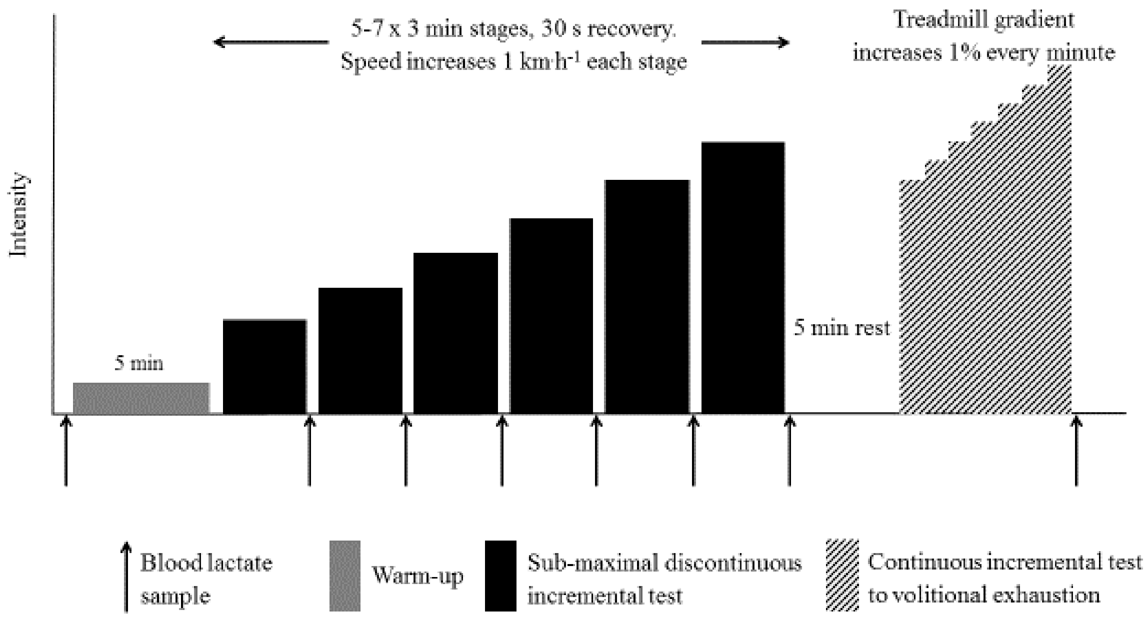


Figure 3.2. Visual representation of the timeline for physiology testing. In this example, six stages are shown for the sub-maximal running assessment, and the maximal test that was terminated at 7 min.

3.5.2 Submaximal Running Assessment

Physiological responses to submaximal running were assessed in accordance with the recommendations for the valid measurement of RE (Shaw et al., 2014) and exercise testing in elite young athletes (Barker and Armstrong, 2011). Following a 5 min warm-up at a speed 2 $km{\cdot}h^{-1}$ slower than the start speed for the assessment, participants completed a discontinuous incremental test involving 5-7 three minute stages on a motorised treadmill (HP Cosmos Pulsar 4.0, Cosmos Sports & Medical GmbH, Munich, Germany). Each stage was interspersed with a 30 s rest for extraction of a capillary blood sample. A judgment of the most appropriate speed for the first stage of the test was made based upon the participant's best race times and published recommendations (Jones, 2009) and provide at least four speeds before LTP. Thereafter, speed was increased by 1 $km \cdot h^{-1}$ every stage until LTP had been surpassed. LTP has been defined as the running speed before the observation of a sudden and sustained increase in BL, occurring between 2-5 $mMol \cdot L^{-1}$ (Midgley et al., 2006a; Smith and Jones, 2001). To avoid the subjectivity associated with identification of LTP via visual inspection of the BL-speed curve, LTP was defined as the speed before a rise of >1 $mMol \cdot L^{-1}$ compared to the subsequent stage. This is consistent with definitions used by other authors (Fletcher and MacIntosh, 2018; Fletcher et al., 2009; Shaw et al., 2013; Thoden, 1991). The gradient of the treadmill was kept at a constant 1% to mimic the effects of outdoor running (Jones and Doust, 1996).

Figure 3.3. Photographs showing examples of physiological testing.

3.5.3 Maximal Running Assessment

Upon completion of the submaximal test, participants dismounted the treadmill and rested passively for 5 min. Participants then completed a continuous incremental test to determine $\dot{V}O_{2max}$ in line with recommended protocol (Barker and Armstrong, 2011; Poole and Jones, 2017). The treadmill speed was set to their sLTP and gradient initially set to 1%. At the end of each minute the gradient increased by 1% until volitional exhaustion was reached, which typically took 6-8 min.

3.6 Physiological Measurements

3.6.1 Anthropometry

Anthropometric measurements were taken according to the International Standards for Anthropometric Assessment (ISAK, 2001). Prior to each running trial, participant's body mass was measured digitally to the nearest 0.1 kg (MPMS-230, Marsden Weighing Group, Oxfordshire, UK). Stature and sitting height were measured with a stadiometer to the nearest 1 cm (SECA GmbH & Co., Hamburg, Germany). Maturity offset was calculated for each participant from age, stature and sitting height values using published formulae (Moore et al., 2015). The sum of skinfolds at four sites (biceps, triceps, subscapula, supra-iliac) was assessed with calipers (Harpenden, Baty International, West Sussex, UK).

3.6.2 Running Economy

Expired air was monitored throughout the sub-maximal and maximal tests via an open circuit metabolic cart (Oxycon Pro, Enrich Jaeger GmbH, Hoechberg, Germany). The automated system measured atmospheric gas concentrations and breath-by-breath gas exchange, thus enabling calculation of pulmonary ventilation, $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$) and the respiratory exchange ratio (RER). Participants breathed through a mask with low-dead space (99 or 125 ml) into a two-way valve with a dual gas sensor. Prior to every test, both gas analysers were calibrated with known concentrations of standard calibration gas (16% O_2; 5% CO_2), and the ventilation measurement unit with a 3 L syringe.

Breath-by-breath data were initially filtered by excluding any breaths which fell outside four standard deviations of the local mean (Lamarra et al., 1987). Filtering was conducted to remove any errant breaths that do not reflect the underlying physiological response. $\dot{V}O_2$, $\dot{V}CO_2$ and RER values were obtained by averaging the final 60 s of each submaximal stage and values for sLTP and the two speeds prior (sLTP-1 $km{\cdot}h^{-1}$, sLTP-2 $km{\cdot}h^{-1}$), were used in subsequent analysis. A 60 s collection period was deemed the longest duration where participants were operating at a steady-state during each stage. To verify whether a steady-state had been achieved during the final minute of each submaximal stage, the difference between the first 30 s of the final minute and the last 30 s was calculated. A difference smaller than the minimal detectable change (MDC), calculated as TE of the mean x 1.96 x $\sqrt{2}$, confirmed a plateau had been achieved. Energy cost of running was estimated from updated non-protein quotient equations (Peronnet and Massicotte, 1991) and the RER values. These values were then added and multiplied by 4.182 to determine total energy cost in kJ. As sLTP varied across participants, RE was expressed as the energy cost of running per km.

The speed(s) at which RE were assessed is important to gain an accurate representation of a runner's rate of energy usage. Although it may seem intuitive to assess a runner at their race pace, for young middle- and long-distance runners these speeds are likely to be above their LTP and therefore a $\dot{V}O_2$ slow component would exist. The presence of a $\dot{V}O_2$ slow component precludes a steady state being attained, thus invalidating measurement of RE (Fletcher et al., 2009; Fletcher and MacIntosh, 2017; Shaw et al., 2014). It is recommended that a range of sub-maximal running speeds are used that are similar to those habitually performed during training (Jones, 2006b).

3.6.3 Blood Lactate

A 20 µl sample of capillary blood was taken from the earlobe at the end of each 3 min stage during the submaximal assessment and upon completion of the maximal test. Each sample was hemolysed and subsequently analysed for BL concentration (Biosen C-Line, EKF Diagnostic, Barleben, Germany). The analyser was calibrated before all trials with a known concentration of BL and in accordance with the manufacturer's instructions. Speed at a fixed BL concentration (sFBLC) was estimated from the speed-lactate curve for 2, 3 and 4 $mMol \cdot L^{-1}$ using published software (Newell et al., 2007).

3.6.4 Heart Rate and Rating of Perceived Exertion

HR was recorded continuously throughout the test (Polar RS400, Polar Electro Oy, Kempele, Finland). Following visual inspection for specious values, data were averaged for the final one minute of each stage and used in subsequent analysis. HR at FBLC was also predicted using a freely available validated spreadsheet (Newell et al., 2007). A rating of perceived exertion (RPE; 6-20 scale) was also taken during the final 30 s of each sub-maximal running stage (Borg, 1982).

3.6.5 Maximal Measures

A participant's $\dot{V}O_{2max}$ was defined as the highest $\dot{V}O_2$ achieved in a 30 s period on the maximal test (after data filtering). Verification that a plateau in $\dot{V}O_2$ had been achieved was identified using the procedure described by Midgley and colleagues (2009). Briefly, a least squared linear regression line was obtained for the $\dot{V}O_2$ data for the period +2 min after commencement of the test to -2 min prior to exhaustion. This period was selected to ensure only the linear portion of the $\dot{V}O_2$ response was captured, avoiding any non-linearity caused by the $\dot{V}O_2$ kinetic response during early stages of exercise and the plateau associated with late stages of a test to exhaustion. $\dot{V}O_{2max}$ was then predicted from this relationship and a plateau was confirmed if the difference between the predicted and actual $\dot{V}O_{2max}$ values was greater than 50% of the regression gradient (Midgley et al., 2009). s$\dot{V}O_{2max}$ was calculated by extrapolating the $\dot{V}O_2$-speed relationship from the sub-maximal running assessment via linear regression. Time to volitional exhaustion was recorded to the nearest second.

3.7 Speed and Biomechanical Testing Protocols and Measurements

Maximal speed and strength-related testing took place in an indoor Tennis hall and biomechanics laboratory respectively. Strength testing consisted of jump-squat testing and an isometric quarter squat to determine dynamic and maximal strength capabilities. A visual representation of the timeline for speed and strength testing is shown in Figure 3.4. Appendix E shows the data recording sheet used for the protocols described in this section. Due to the lack of familiarity with several of the movement patterns used to assess strength capabilities, all participants who were assessed completed a familiarisation session prior to the first data collection trial.

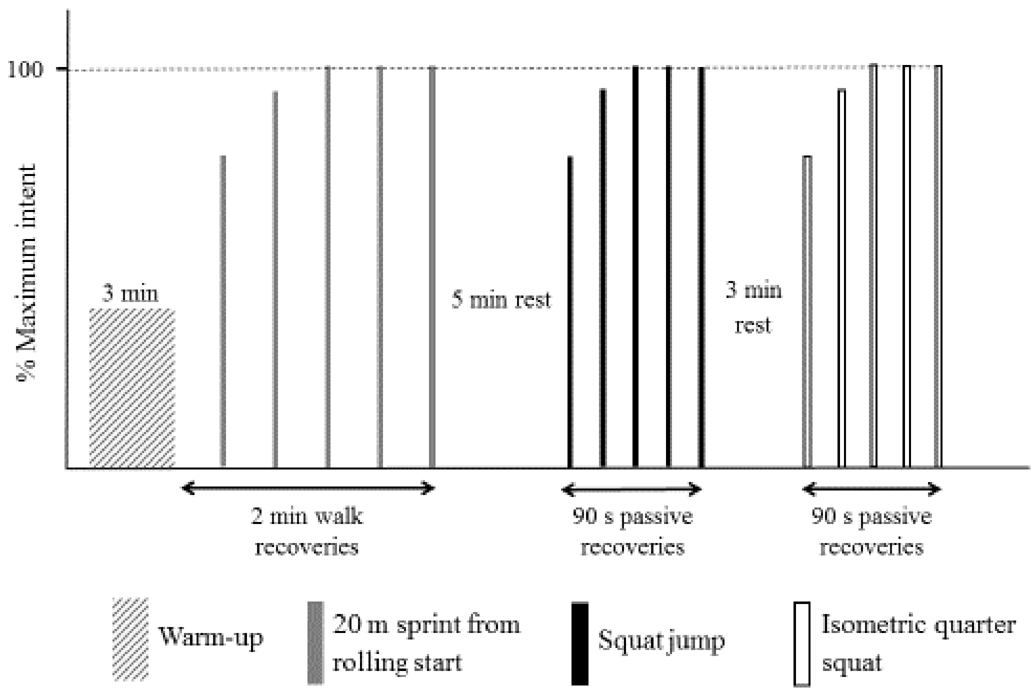


Figure 3.4. Visual representation of the timeline for speed and biomechanics testing. Prior to each test, two warm-up repetitions were permitted, one instructed to be performed at three-quarters of maximum effort, and one at close to maximum intent. Three maximal attempts were performed on each test.

3.7.1 Maximal Speed

Following a self-paced 3 min warm-up run, participants performed two sub-maximal 20 m sprints from a rolling start, followed by three maximal timed sprints (Brower Timing Systems, Utah, USA). Each sprint was interspersed by a 2 min walk recovery. Participants were instructed to initiate their sprint with a sufficiently long approach to enable maximal speed to be reached by the first set of timing gates. The best score over the three attempts was used in subsequent analysis for each test.

3.7.2 Squat Jump

To assess dynamic strength capabilities, participants performed three squat jumps for maximum height on a fixed force plate sampling at 1000 Hz (Kistler 9287BA, Kistler Instruments Ltd, Hampshire, UK). Following two warm-up repetitions, each attempt was separated by a 90 s passive recovery. Participants were instructed to place their hands on their hips and squat down to a half-squat position (90^{o} knee flexion) determined from visual inspection, hold this position for 3 s, and on a signal provided by the tester, jump as high as possible. If there was an indication on the force trace that a counter-movement had been used prior to initiation of the jump, the attempt was repeated. Peak displacement of the centre of mass was estimated using the velocity at take-off method (Moir, 2008). In brief, velocity at each time point (0.001 s) was calculated (Microsoft Excel, 2013) using the equation: (net force/body mass) x time, where net force equals the difference between the absolute force reading and body weight (N), and time equals 0.001 s. RFD was calculated for every time point of the jump as (force value – last force value) / 0.001. Peak vertical ground reaction force ($vGRF_{jump}$) and peak RFD were recorded as the highest values produced during the concentric phase of the jump, identified visually on the force-time graph. The highest jump, $vGRF_{jump}$ and peak RFD values from the three attempts were used in subsequent analysis.

3.7.3 Isometric Quarter Squat

MVC was assessed in a custom built adjustable back-squat rig (Figure 3.5). Participants gripped a fixed bar, positioned across their upper back, and adopted a quarter-squat position with knees flexed at 140^{o}. This position was determined during the familiarisation session using a goniometer (Jamar 7514, Patterson Medical, Nottinghamshire, UK), thus an identical set-up was used in subsequent trials. Participants stood on a force plate (PASPORT PS2141, PASCO, Roseville, CA, USA) measuring at 1000 Hz and were instructed to push against the bar as hard as possible for 3-4 s. Two warm-up repetitions preceded three recorded attempts in which strong verbal encouragement was provided. Attempts were each separated by 90 s of rest. MVC was defined as the highest force value produced during the contraction. The best score over the three attempts was taken forward and used in later analysis.

Figure 3.5. Equipment set-up for isometric quarter squat test.

3.8 Statistical Analysis

Data are displayed as mean ± SD and significance was accepted at $p<0.05$. The parametric properties of data and all hypothesis-based testing was carried out in SPSS Statistics (version 22, IBM, New York, USA).

MDC values can be used for practical interpretation of the change required in measurements to have 95% certainty that real change has occurred. MDC confidence intervals (MDC_{95}) were calculated for each variable as TE x 1.96 x $\sqrt{2}$ (Weir, 2005). TE, MDC and ES values were all calculated in Microsoft Excel 2013. Effect sizes are interpreted as trivial <0.20; small 0.20-0.59; moderate 0.60-1.19; and large ≥ 1.2 (Batterham and Hopkins, 2006).

To facilitate more widespread use of findings in applied settings, magnitude based inference (MBI) terms were identified where appropriate, to provide a more qualitative interpretation of the extent to which differences or changes observed were meaningful. MDC_{95}, values were entered along with corresponding *p*-values and the mean difference between groups into a published spreadsheet (Batterham, 2003) to obtain the likelihood that the intervention was beneficial (or indeed harmful) to the population. The spreadsheet was used to convert the *p*-value into a confidence interval for the mean difference, which provided an inference of the true value of the effect observed. The MDC_{95} represents the magnitude required for a change in score to be considered practically meaningful, and therefore provided a robust threshold to judge the efficacy of an intervention. The resulting values were translated into descriptors using the modified thresholds proposed in the literature (Batterham and Hopkins, 2006): 0-0.5% most unlikely; 0.5-5% very unlikely; 5-25% unlikely; 25-75% possibly; 75-95% likely; 95-99.5% very likely; and >99.5% most likely.

Inter-individual responses to an intervention were considered by calculating the true individual difference in response using the following formula:

$$\sqrt{SD_{Int}^2 - SD_C^2}$$

Where SD_{Int} and SD_C represents the SD of the change score for the intervention and control condition (or CG) respectively (Atkinson and Batterham, 2015).

CHAPTER 4

STRENGTH AND CONDITIONING HABITS OF COMPETITIVE MIDDLE- AND LONG-DISTANCE RUNNERS

(Study 2)

Published papers from this chapter:

Blagrove, R. C., Brown, N., Howatson, G. and Hayes, P. R. (2017) Strength and conditioning habits of competitive distance runners. *The Journal of Strength and Conditioning Research*. Published ahead of print. Doi: 10.1519/JSC.0000000000002261

4.1 Introduction

Middle- and long-distance runners typically utilise long slow distance, threshold tempo, and interval running to train the physiological variables that underpin their performance (Seiler, 2010). Although it is well-established that these methods of training will provide an improvement in performance (Midgley et al., 2007a), there is also evidence that bi-weekly ST sessions can enhance TT performance and several important physiological parameters (Beattie et al., 2014). In particular, RE has shown improvement following 6-8 weeks of ST for a range of ages and training levels (Denadai et al., 2017). For well-trained distance runners, RE tends to predict performance more accurately than $\dot{V}O_{2max}$ (Conley and Krahenbuhl, 1980), and requires lengthy periods of endurance training to generate improvements (Midgley et al., 2007). ST therefore potentially offers a time efficient strategy to improve RE in this sub-population.

S&C should also form part of a well-rounded approach to the long-term development of adolescent athletes (Bergeron et al., 2015), and is recommended for young distance runners (Mikkola et al., 2007). Equally, older athletes benefit from RT (Tayrose et al., 2015), and improvements in RE have been observed following a period of ST in masters marathon runners (Piacentini et al., 2013). Despite these findings, it is uncertain what proportion of runners currently engage with ST, and whether runners of a specific age and competitive status are more likely to participate.

It is estimated that up to 70% of competitive runners sustain an injury, which prevents them training for at least one week, each year (Hreljac, 2004). Risk factors for injury in runners, such as reduced flexibility (Yagi et al., 2013), muscular weakness and asymmetry (Fredericson, 1996; Mucha et al., 2017; Niemuth et al., 2005), and neuromuscular control (Franettovich et al., 2014) can potentially be addressed with a targeted programme of S&C. It is currently unknown whether endurance runners participate in training activities to enhance these qualities in the belief that injury risk could be reduced. Other injury prevention and recovery strategies such as core stability exercises, stretching, and foam rolling are also popular with athletes (Cheatham et al., 2015; Leppänen et al., 2014; Murray et al., 2017; Wirth et al., 2017), however the degree to which these modalities are used by distance runners is also uncertain.

A number of studies have documented the training practices of distance runners (Bale et al., 1985; Hewson and Hopkins, 1995; Karp, 2007; Knechtle et al., 2011; Voight et al., 2011; Young and Salmela, 2010), however only three papers mention the runners engagement with S&C related activities (Karp, 2007; Voight et al., 2011; Young and Salmela, 2010). In a cohort of 50 non-elite marathon runners, it was reported that 24% included weight lifting as part of their marathon preparation, increasing to 40% in the month after the event (Voight et al., 2011). Similarly, in a group of 93 marathon runners, just over half included ST in their programs (Karp, 2007). It is unclear whether the same trends in participation exist for runners who compete over shorter distances. A retrospective questionnaire in 48 middle-distance runners showed that runners of a higher qualification (national standard) accrued greater cumulative minutes of ‘endurance-weights’ compared to lower standard (provincial and club standard) runners after three, five and seven years, with the gap widening as time progressed (Young and Salmela, 2010). Interestingly, differences between groups were not evident prior to the start of the runner’s careers and no differences were noted between groups for total training time.

4.1.1 Study Aims

This thesis has established the effect of ST on performance and important physiological determinants in distance runners (Study 1). There are currently no studies that have specifically investigated the S&C practices of distance runners. Such information could be used to understand the impact of the current scientific knowledge, support the rationale for other studies in this thesis and influence the development of professional coaching courses and programmes of education for the coaches of athletes. Therefore, the primary aim of this study was to identify the extent to which distance runners engage with S&C and the characteristics of those who participate in various activities. This specifically relates to the second objective of this thesis. The study also aimed to examine whether reported injury rates relate to the training behaviours of runners.

4.2 Methods

4.2.1 Study Design

A four-part, 16-question survey (see Appendix F) was administered to a convenience sample of distance runners (0.8 km – ultra-distance) to anonymously identify their typical running behaviour and S&C practices. The survey was designed in collaboration with two S&C coaches, a running coach, an exercise physiologist, and an academic who specialises in survey design. Following targeted pilot testing with ten runners of varying age and competitive level, there was further refinement of questions.

Questions that are partly understood or misinterpreted by participants due to low literacy levels are likely to generate invalid and unreliable data (Paz et al., 2009). It is therefore recommended that surveys intended for distribution to the general public do not include questions that require >8 years of formal schooling (Calderón and Beltrán, 2004), and have a Flesch readability score of >60 (equivalent to a Flesch-Kincaid score of 7.0). As this survey intended to target participants aged ≥ 15 years, the readability was adjusted to ensure comprehension by a wide audience. The readability of the survey was assessed prior to use and deemed appropriate for individuals aged over 12 years (Flesch reading ability score: 71.2). The survey was available online via the Bristol Online Survey platform for a period of 12 months (April 2016 to March 2017).

4.2.2 Participants

In addition to institution level ethical clearance, approval was also obtained from the *parkrun* research project board to advertise the survey via their newsletter. The survey was open to any distance runners age 15 years old and above. The title page of the survey included information on the purpose of the study and a statement of consent, which participants were required to agree to in order to progress to the questions. A parent/guardian of participants under the age of 18 provided a statement of consent, which was sent via email to the author. Participants were also recruited via running pages on social networking websites and emails sent to coaches, clubs and runners worldwide through the contacts acquired by the author.

4.2.3 Procedures

The survey was split into four sections and contained fixed-response questions, which generated categorical and ordinal data. Section one of the survey identified participant demographics and section two contained a series of questions concerning their typical running habits. The third section of the survey required participants to detail their typical S&C practices. Items relating to how participants learned about the most appropriate techniques was also included (section four).

4.2.4 Statistical Analysis

Training behaviour questions were cross-tabulated with participant characteristics and injury frequency using Chi-squared (χ^2) tests of independence. Fishers exact statistic was used if the expected response count was <5. Where significance was detected, follow-up *post-hoc* tests were performed using a Bonferroni Correction via the adjusted standardised residuals. Multinomial logistic regression was used to model the predictive capacity of training behaviours on injury frequency and calculate adjusted odds ratios with associated 95% confidence interval (CI). Binary logistic regression (forward method) was applied for questions relating to participation in S&C activities, as responses were dichotomous.

4.3 Results

4.3.1 Characteristics of Respondents

A total of 1883 surveys were completed. To filter those respondents who were not competitive distance runners, and therefore potentially perform S&C for other sports or recreational reasons, participants who answered '*I only participate and don't compete'* to a competitive level question were excluded from analysis. The competitive level and age-distribution of the remaining 667 runners (male n=383; female n=284) are presented in Table 4.1 and Figure 4.1 respectively. The majority (67.3%) of runners surveyed competed at longer distance events (5 km – half-marathon), however under-20 and under-17 runners were mainly middle-distance (0.8 - 3 km) specialists (76.5%). More than 75% of the respondents typically ran ≤ 64 km per week (Figure 4.2). However, there was a significant difference between competitive level and average reported running volume (χ^2(20)=188.8, p<0.001), with local club runners tending to run ≤ 64 km per week (p<0.001), national standard runners 65-96 km per week (p<0.001) and international runners > 129 km per week (p<0.001). Seventy percent of runners performed high-intensity running (interval training and tempo running) 1-2 times per week and a further 20% performed 3-4 sessions per week of this nature.

Table 4.1. Competitive level of male and female respondents (n=667).

	Local club	**County**	**Regional**	**National**	**International**
Male	271 (70.8%)	28 (7.3%)	33 (8.6%)	30 (7.8%)	21 (5.5%)
Female	200 (70.4%)	27 (9.5%)	14 (4.9%)	28 (9.9%)	15 (5.3%)
Total	471 (70.6%)	55 (8.2%)	47 (7.0%)	58 (8.7%)	36 (5.4%)

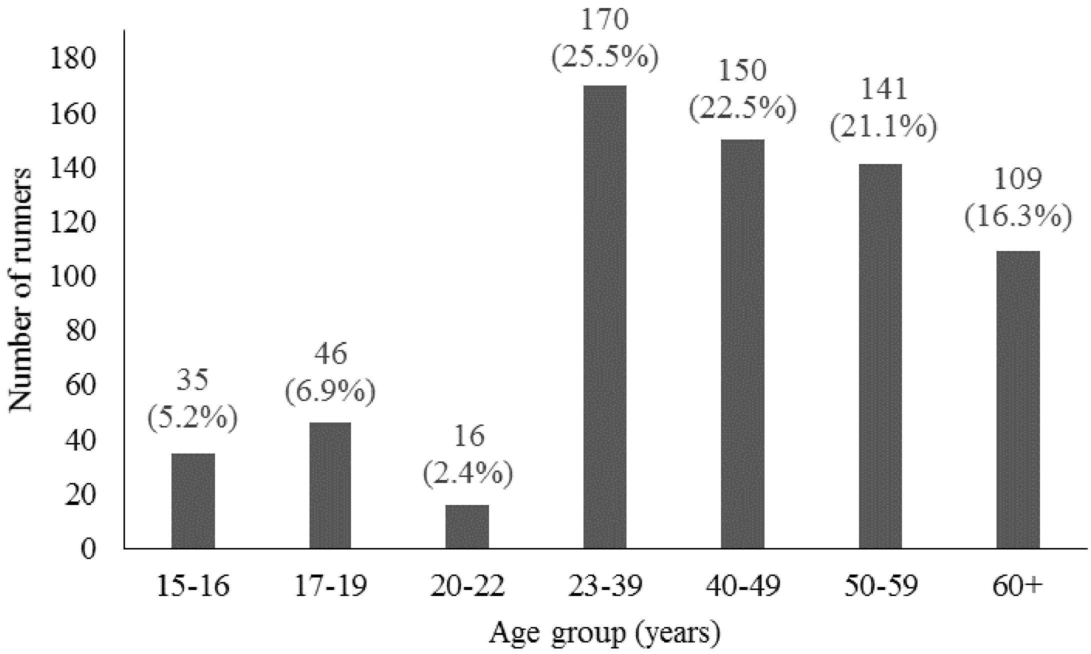


Figure 4.1. Age distribution of competitive runners (*n*=667).

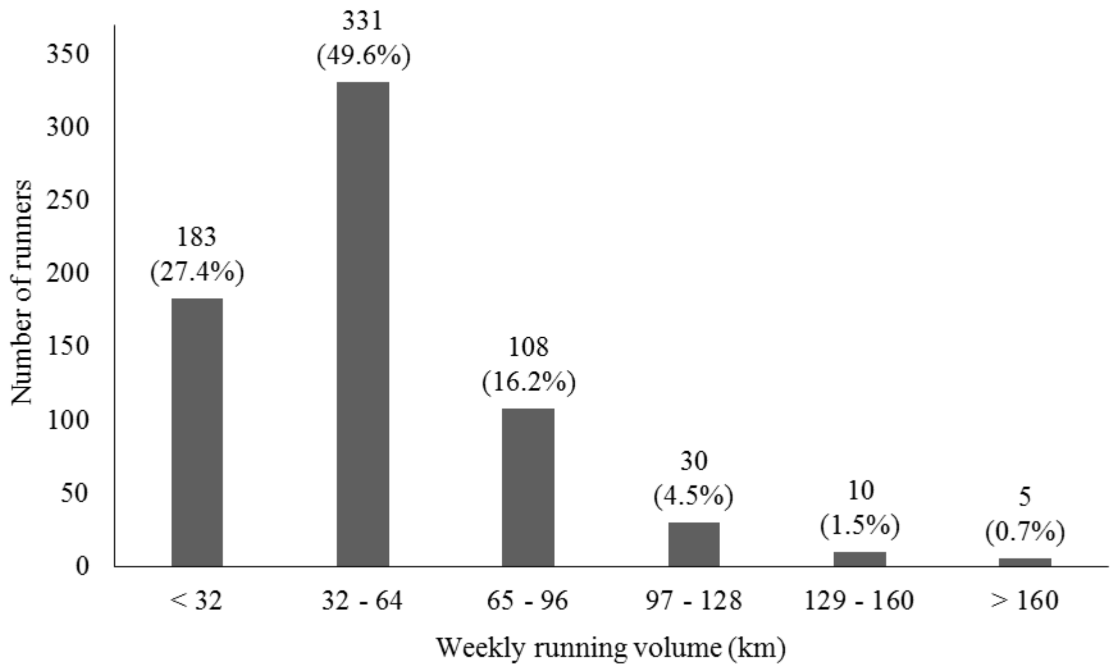


Figure 4.2. Typical weekly running volume of competitive runners (*n*=667).

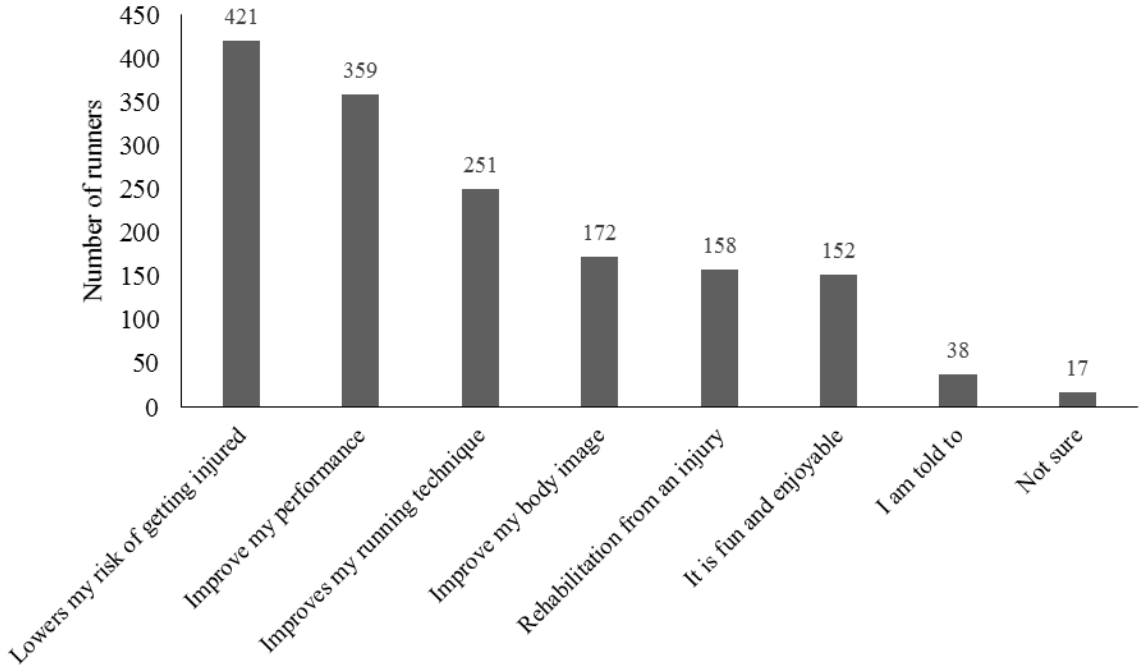


Figure 4.3. Reasons that runners include S&C activities as part of their training (multi-response question).

4.3.2 Engagement with Strength and Conditioning

The reasons that runners included S&C activities in their training routines are presented in Figure 4.3. Across all ages and competitive levels, runners typically performed S&C activities to improve their performance (53.8%) and lower their risk of sustaining an injury (63.1%).

Table 4.2 shows the engagement with S&C activities, and for those who included each activity, the typical prescription they adopted. The most commonly used S&C activities were stretching (86.2%) and core stability exercises (70.2%). For those who included each activity, there were no differences in the frequency, duration or timing of the activities across age groups or competitive levels (p>0.05). A runners sex did not discriminate whether they participated in RT or PT, but more females than males included circuit training (38.0% vs 19.0%, p<0.001), stretching (90.1% vs 83.3%, p=0.011) and core stability (74.7% vs 66.8%, p=0.029) in their programmes.

Only 35.1% of runners utilised PT as part of their training. A disproportionately high number of under-17 (p=0.01) and under-20 (p<0.001) runners and a lower number of masters 50-59 and 60+ years (p<0.05) incorporated this activity ($\chi^2(6)$=34.40, p<0.001) as illustrated in Figure 4.4. A significant difference was also detected for the standard of runner who utilised PT ($\chi^2(4)$=34.56, p<0.001, Figure 4.5), with significantly fewer local club standard runners using this modality (p<0.001) and significantly more regional, national and international runners taking part in the activity (p<0.001). A logistic regression model was statistically significant, ($\chi^2(3)$=38.77, p<0.001), but age category, competitive distance and level and could only explain 7.8% (Nagelkerke R^2) of the variance in whether runners performed PT or not. The model correctly classified 62.5% of cases, with under-20 runners associated with a low likelihood of not participating (odds ratio (OR): 0.35, 95%CI: 0.15-0.83, p=0.017). An international runner was 3.13 times (95%CI: 1.24-7.92, p=0.016) more likely to include PT than a county standard runner.

Approximately 60% of runners used RT, and cross-tabulation analysis detected a significant difference for those who utilised RT and the standard of runners ($\chi^2(4)=16.43$, p=0.002, Figure 4.5). Post-hoc analysis revealed a significantly small proportion of local club runners took part in RT ($p<0.001$), but a high number of national ($p<0.05$) and international ($p<0.05$) runners participated. A logistic regression model was statistically significant, ($\chi^2(3)=16.90$, p=0.001), for age, race distance and competitive level as explanatory factors for whether runners participated in RT. Age group and race distance had poor predictive power ($p>0.05$) but competitive level alone classified 62.5% of cases correctly. An international runner was 3.37 times (95%CI: 1.27-8.92, p=0.014) more likely to take part in RT compared to a local club runner.

Fundamental movement skills were used by only 27.7% of the runners surveyed, however 47.2% of the international runners made use of this activity, which represented a higher proportion than other competitive levels ($p<0.01$). Running technique drills were used by half (50.4%) of the runners surveyed with under-17 and under-20 runners using them more than older age groups ($p<0.001$), and higher standard (regional, national and international) runners using them more than lower standard ($p<0.002$). Logistic regression showed an international runner was 3.59 times (95%CI: 1.69-7.60, p=0.001) more likely to perform running drills compared to a local club runner. Bodyweight exercises were used by 60.4% of runners with senior runners using them more so than other age categories (p=0.002). Circuit training was used by a small number of runners (27.1%) but a high proportion of junior (under-17 and under-20) runners used this technique compared to older age groups ($p<0.001$).

Stretching was included in the programmes of most runners (86.2%) of all age and ability. Runners typically stretched for <15 min, after running sessions at a higher frequency than other S&C activities. Core stability exercises were also widely used (70.2%) across all age categories but tended to be less used by local club runners (p=0.004) compared to other standards of runners. An international runner was 3.07 times (95%CI: 1.17–8.05, p=0.023) more likely to use core stability exercises than a local club runner. Few runners use barefoot exercises in their training routine (14.8%).

For many S&C activities (RT, PT, running drills, circuit training and barefoot exercises) engagement was significantly higher in those who competed in middle-distance (0.8 - 3 km) events compared to long-distance (5 km-half marathon) runners ($p<0.001$). For example, middle-distance specialists were 2.67 times more likely to participate in RT compared to a long-distance runner, and 6.68 times more likely than an ultra-distance runner. Similarly, middle-distance runners were 3.53 times more likely to perform PT and 4.26 times more likely to include running drills compared to those in the long-distance category.

4.3.3 Injury

Overall, 67.4% of runners had suffered at least one injury in the last year. Cross-tabulation revealed a positive association between number of injuries and both typical mileage ($\chi^2(25)=44.7$, $p<0.001$) and running frequency ($\chi^2(25)=41.0$, $p<0.001$). A significant difference was detected between injury rate and runners participation in RT ($\chi^2(5)=15.2$, $p=0.010$), bodyweight exercises ($\chi^2(5)=21.3$, $p=0.001$), stretching ($\chi^2(5) = 18.9$, $p=0.002$), foam rolling ($\chi^2(5)=29.8$, $p<0.001$) and core stability exercises ($\chi^2(5)=13.5$, $p=0.019$). Specifically, post-hoc analysis showed that of those who had not sustained any injuries in the last year, a small number participated in each of these activities ($p<0.001$). A multinomial logistical regression for typical mileage, running frequency and participation in these five S&C activities could explain 20.2% (Nagelkerke R^2) of the variance in response to injury rates, however no factors in their own right were able to predict any level of injury incidence.

Table 4.2. Frequency of respondents who use strength and conditioning (S&C) activities and the typical prescription of each activity. Percentages identified are based upon only those who use each activity.

Activity	Number who participate	Frequency (per week)	Duration of activity per session	Positioning of activity in training routine
Stretching	575 (86.2%)	1-4 (66.2%)	<15 min (64.5%)	After running (56.9%)
Core stability	468 (70.2%)	1-2 (68.9%)	<30 min (80.8%)	Independent session (45.9%) or part of S&C session (41.2%)
Resistance training	417 (62.5%)	1-2 (81.0%)	<30 min (56.6%)	Independent session (44.3%) or part of S&C session (42.3%)
Bodyweight exercises	403 (60.4%)	1-2 (70.6%)	<30 min (75%)	Independent session (46.5%) or part of S&C session (36.8%)
Foam rolling	365 (54.7%)	1-2 (74.5%)	<15 min (74.5%)	Independent session (46.6%) or after running (43%)
Running drills	336 (50.4%)	1-2 (77.4%)	<15 min (61.3%)	Warm-up (68%)
Plyometric training	234 (35.1%)	1-2 (89.3%)	<15 min (66.7%)	Part of S&C session (35.8%) or warm-up (34.9%)
Balance training	211 (31.6%)	1-2 (81.6%)	<15 min (70.1%)	Part of S&C session (45.6%) or independent session (39.4%)
Fundamental movement skills	185 (27.7%)	1-2 (69.1%)	<15 min (55.6%)	Warm-up (40.2%) or part of S&C session (32.2%)
Circuit training	181 (27.1%)	1-2 (87.4%)	15-45 min (58.9%)	Independent session (58.6%)
Barefoot exercises	99 (14.8%)	1-2 (76.1%)	<15 min (73%)	Independent session (34.4%) or part of S&C session (34.4%)

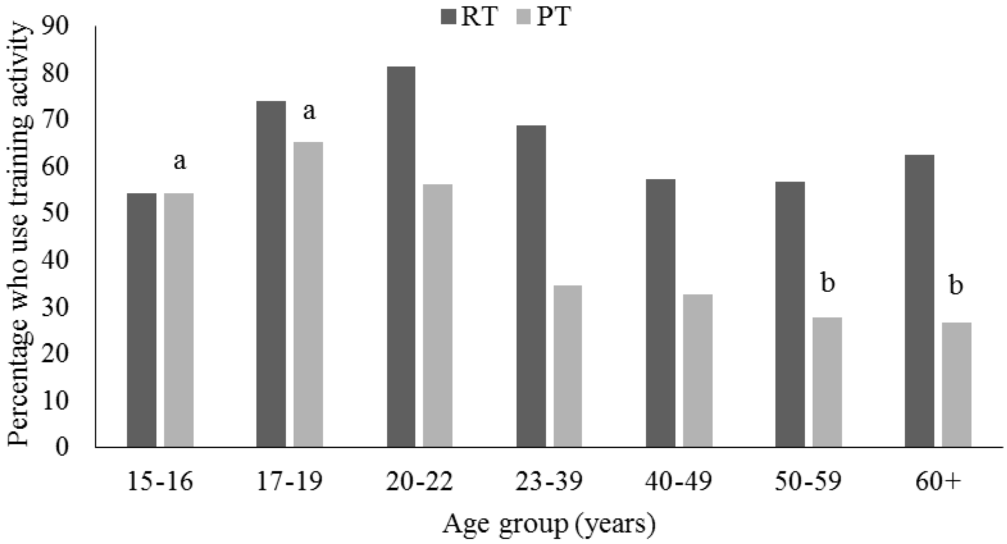


Figure 4.4. Percentage of respondents in each age category who participate in resistance training (RT) and plyometric training (PT). [a] significantly higher participation than the Chi-squared expected frequency ($p \leq 0.01$), [b] significantly lower participation than the Chi-squared expected frequency ($p<0.05$).

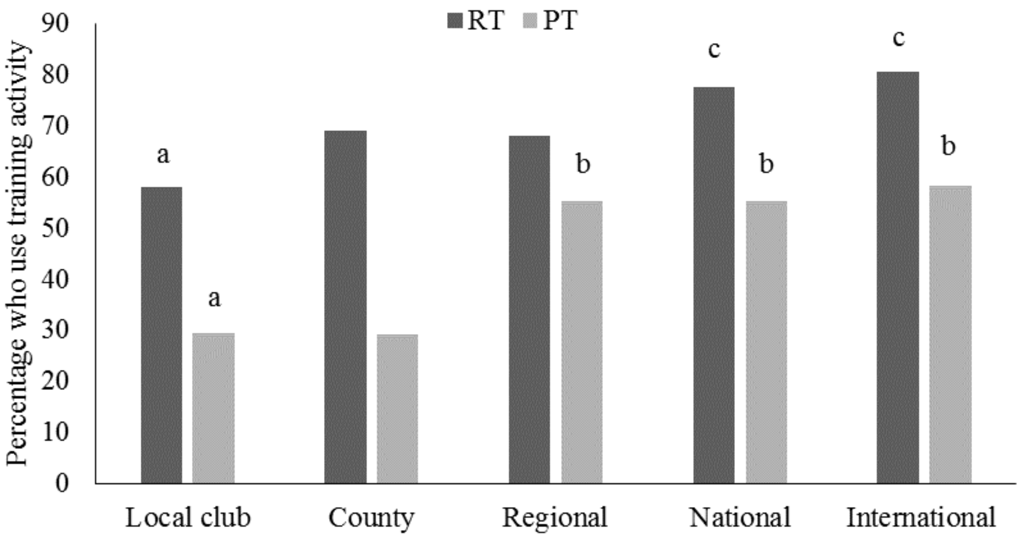


Figure 4.5. Percentage of respondents in each competitive category who participate in resistance training (RT) and plyometric training (PT). [a] significantly lower participation than the Chi-squared expected frequency ($p<0.001$), [b] significantly higher participation than the Chi-squared expected frequency ($p<0.001$), [c] significantly higher participation than the Chi-squared expected frequency ($p<0.05$).

4.4 Discussion

This is the first study to document the S&C practices of competitive distance runners. Runners who engaged in S&C activities were mainly motivated by improving their performance and lowering their risk of injury. Stretching and core stability were the most popular activities, however almost two-thirds of runners perform regular RT, including a high proportion of junior (under-20) runners. Middle-distance specialists and runners who compete at a higher level were most likely to perform S&C activities. Participation in S&C does not seem to be associated with lower injury rates but higher running training volumes appear to be related to the number of injuries runners experienced.

Stretching and core stability exercises were used by a high proportion of runners (86.2% and 70.2% respectively) despite a lack of evidence showing these strategies are effective at reducing injury risk (Baxter et al., 2017; Huxel Bliven and Anderson, 2013; Leppänen et al., 2014; Small et al., 2008), enhancing recovery (Baxter et al., 2017) and improving performance (Baxter et al., 2017; Wirth et al., 2017). Foam rolling was also used by 54.7% of runners mainly after training sessions or as an independent session, which can be effective for enhancing recovery and improving range of motion (Cheatham et al., 2015). In a group of 112 elite adolescent athletes, 68% and 38% of respondents included stretching and foam rolling as a recovery modality respectively, which is lower than the participation reported here for both the whole cohort of competitive runners and juniors only (Murray et al., 2017).

Over half (53.8%) of those surveyed perform S&C activities with the goal of improving performance, and 76.9% of those runners include ST (RT and/or PT) in their programmes. Although extensive research supports the benefits of ST on several determinants of distance running performance (Beattie et al., 2014; Denadai et al., 2017), few studies have reported the extent to which runners engage with these activities. Of the competitive runners surveyed, 62.5% included RT in their programmes and 35.1% used PT. Depending upon the exercise selected and training-status of the runner, bodyweight exercises (60.4% participation rate) may also provide sufficient overload in non-strength trained individuals to induce neuromuscular adaptation and thus improve strength qualities.

Evidence suggests a training frequency of two ST sessions per week is required to obtain benefits (Beattie et al., 2014; Denadai et al., 2017), however one session per week has also shown positive outcomes if high-intensity exercises are used (Berryman et al., 2010; Ferrauti et al., 2010). The ST performed appears to be in-line with this recommendation as most runners reported they typically perform both RT and PT 1-2 times per week as independent sessions or as part of an S&C session. This volume of work is also the same as previously reported for a group of well-trained Spanish runners (Esteve-lanao et al., 2005).

S&C activities are recommended for adolescent athletes to develop a wide-range of physical competencies, improve neuromuscular co-ordination and enhance performance (Lloyd et al., 2014). The engagement within the under-17 and under-20 age groups across all S&C modalities was significantly higher compared to the overall participation rate for each activity, and for PT (Figure 4.4), running drills and circuit training, participation was significantly greater than for older age groups. There is currently a lack of literature which directly examines the impact of ST on young distance runners specifically, however sprint performance (5-40 m) has been shown to be positively affected in males (Rumpf et al., 2012).

The competitive level of participants was linked to engagement with RT, PT (Figure 4.5) and fundamental movement skills, which is in agreement with findings from others (Karp, 2007; Young and Salmela, 2010) who observed that national/international male runners performed more ST than those competing at a lower standard. Benefits of ST activities have been reported for runners of all abilities (Denadai et al., 2017), however the barriers to participation amongst lower standard runners are not known. Time-constraints, fatigue, a lack of knowledge and the cost associated with facility access have been cited as reasons for non-participation in physical activity (Trost et al., 2002), therefore if these same barriers exist for ST in runners, practitioners should devote time to educating their athletes and finding innovative strategies to improve engagement.

There was a tendency for middle-distance runners to participate in S&C activities to a greater degree than runners who compete over longer-distances. Shorter events require a greater contribution from anaerobic energy sources (Houmard et al., 1991), therefore middle-distance specialists are perhaps more likely to include ST in their programmes, which has been shown to enhance speed (Mikkola et al., 2007; Ramírez-Campillo et al., 2014) and anaerobic parameters in runners (Paavolainen et al., 1999). Nevertheless, RE is an important factor for any middle- (Brandon, 1995) or long-distance runner (Sparling, 1984) and has consistently been shown to improve following a period of ST (Denadai et al., 2017). Therefore all distance runners should consider including ST modalities in a well-rounded training regimen, regardless of event specialism.

Runners mainly chose to include S&C in their programme in the belief it lowers the risk of injury (63.1%). The mechanisms of injury are multi-faceted and complex, however several modifiable risk factors have been identified for common overuse injuries in runners, including gluteal weakness (Mucha et al., 2017; Niemuth et al., 2005), neuromuscular control (Franettovich et al., 2014), asymmetry (Fredericson, 1996) and low bone mineral density (Warden et al., 2014). RT, particularly for musculature around the hips, has been shown to be effective at minimising the risk of some types of overuse injury (Willy and Davis, 2011). Studies conducted on injury prevention approaches using athletes from other sports have also shown balance training and warm-ups that utilise neuromuscular control exercises to be effective at reducing certain injuries (Leppänen et al., 2014; Myer et al., 2011; Steib et al., 2017). Less than a third (31.6%) of runners included balance training in their programmes, and a similar number indicated they include neuromuscular control type activities (fundamental movement skills and PT) in their warm-up routine, however it is unknown whether these activities specifically are reducing injury risk in runners.

A greater weekly mileage and training frequency were associated with higher rates of injury, which is in agreement with risk factors identified by others (van Gent et al., 2007). Of the runners who reported no injuries, a low proportion participated in some S&C activities (RT, bodyweight exercises, stretching, foam rolling, core stability). There was also a significant link between those who reported running the highest volume and participation in these S&C activities. When S&C participation and running volume variables were entered into a logistical regression model, they could only explain a small proportion of the variance in injury rates reported by runners (20.2%). This suggests that although a link may exist between injury rates and each factor, they are likely to be independent of one another.

4.4.1 Limitations

A number of limitations are important to acknowledge for a study of this nature. Survey response data provides meaningful information on the association between specific characteristics of respondents and participation in S&C activities, however this does not imply causality. Therefore the data can only be used to determine patterns in participation and whether this aligns to recommendations from scientific literature. Similarly, the study cannot ascertain the reasons a runner does not participate in S&C activities, which would be useful information to aid coaches with increasing engagement. Although a relatively large sample size was obtained for this study, this doesn’t completely eliminate the potential for bias created by convenience sampling. It is also possible that despite our best efforts to maximise the readability of the survey, some questions may have been misinterpreted, thus producing inaccurate data. Similarly, there is also the potential that some recall bias may exist within the responses to retrospective self-reporting questions. Finally, non-competitive participants were excluded from data analysis to reduce the likelihood that they performed S&C activities for other sports or reasons, however this possibility cannot be completely eliminated.

4.4.2 Conclusions

Competitive distance runners who include S&C activities in their training routine are mainly motivated by lowering risk of injury (63.1%), and improving performance (53.8%). The most common activities utilised were stretching (86.2%) and core stability exercises (70.2%), whilst RT and PT were used by 62.5% and 35.1% of runners respectively. Junior (under-20) runners include PT, running drills and circuit training more so than masters runners, and international standard runners participate in RT, PT and fundamental movement skills training to a greater extent than competitive club runners. Middle-distance specialists were more likely to include RT, PT, running drills, circuit training and barefoot exercises in their programme than longer-distance runners. Injury frequency was associated with typical weekly running volume and run frequency, but S&C did not appear to confer a protection against the number of injuries runners experienced.

4.5 Perspective

This thesis aims to investigate the engagement with, and efficacy of, strength-based exercise in distance runners, with a focus on adolescent performers. A comprehensive systematic review (Study 1, Section 2.5) provided evidence for the benefits of ST in middle- and long-distance runners. However, despite this collection of scientific research, which spans almost 20 years, it was unknown what types of distance runner (if any) were participating in ST activities. The results of this study have therefore contributed to addressing the overall objective of this thesis by describing the nature of engagement with S&C activities in a large cross-section of the competitive distance running community (n=667, ≥ 15 years old) based upon the responses to an online survey. The findings of this study have presented a number of avenues for novel research enquiry (see Section 8.4) and provide further rationale for the subsequent agenda of studies proposed in this thesis.

Junior (under-20) runners participate in ST activities more so than older age-groups, despite the lack of literature that has specifically investigated this sub-population. This indicates that time invested in original research in this age-group would be valuable. Moreover, the late-adolescence period, where young athletes typically elect to specialise in a single sport has been highlighted as being crucial (Lloyd et al., 2016; Lloyd and Oliver, 2012; Myer et al., 2016). Complementing running-based training with ST activities may therefore assist young distance runners in maximising their potential during this period of their development.

Interestingly, of those distance runners that include PT in their training routine, a similar percentage perform their exercises as part of an S&C session (35.8%) as a warm-up (34.9%) before a running session. It is perhaps likely that these PT exercises are not high-intensity in nature, but their inclusion has the potential to provide a potentiation response if prescribed appropriately for middle-distance runners who possess specific characteristics (see Section 2.6). This finding contributes further to the rationale for Study 5, which aims to investigate the acute effect of a LCA on RE and TTE in adolescent male distance runners.

Based upon the literature reviewed (Chapter 2) and findings of this study, it is speculated that strength-based exercise will provide chronic and acute benefits to performance-related outcomes in adolescent post-pubertal distance runners. To address the aims of studies 4 and 5 in a robust manner, any physiological and biomechanical data collected must be valid and reliable. It is therefore necessary to conduct a reliability study in the population under investigation, which addresses previous issues associated with accurate quantification of physiological and biomechanical parameters, to ascertain the TE of measurement.

CHAPTER 5

RELIABILITY OF PHYSIOLOGICAL- AND STRENGTH-RELATED PARAMETERS IN ADOLESCENT DISTANCE RUNNERS FOLLOWING ALLOMETRIC SCALING

(Study 3)

Published papers from this chapter:

Blagrove, R. C., Howatson, G. and Hayes, P. R. (2017) Test-retest reliability of physiological parameters in elite junior distance runners following allometric scaling. *European Journal of Sport Science*, 17(10), pp. 1231-1240.

5.1 Introduction

To have a reasonable degree of confidence that an observed change in a physiological or biomechanical measure is meaningful following exposure to an intervention, it is important to determine the systematic and biological error associated with that measure, and hence what should be considered real change (Atkinson and Nevill, 1998). Practitioners also rely on data acquired from physiological and biomechanical testing to individualise athlete training load and make inferences concerning fatigue status and readiness to perform (Halson, 2014). Providing accurate recommendations to athletes and their coaches can be problematic unless the reliability of the measurement tools has been established, which is particularly important when confounding factors such as lifestyle and diet are not well-controlled.

Competitive adolescent distance runners are likely to undertake relatively high-volumes of training for their age (Solomon et al., 2017; Wilson et al., 1999) and are potentially exposed to a variety of non-training stressors such as school work and expectations imposed by significant others (Winsley and Matos, 2011). It is likely that this stress will impact physiological status via hormonal and chemical imbalances (Meeusen et al., 2013), therefore determining day-to-day variability in measurements is crucial. The tempo and timing of biological maturation is highly variable in adolescents and periods of accelerated physical development have been associated with disruptions to motor coordination (Beunen and Malina, 1988). Therefore maturational status has the potential to influence the short-term stability of physical performance measures in young athletes compared to adult runners.

Substantial variability in patterns of growth and maturation in young athletes mean that using a conventional ratio scaling approach to partitioning body mass is theoretically and statistically inappropriate (Eisenmann et al., 2001). Therefore, a factor that may influence the reliability metrics reported in previous studies relates to the method that is employed to scale for variations in body mass amongst participants.

5.1.1 Physiological Measurements

Distance running performance is determined by several important physiological qualities including $\dot{V}O_{2max}$, RE and speed at various points on a lactate curve (Bassett and Howley, 2000; Sparling, 1984). Well-established treadmill testing protocols are used to evaluate the efficacy of training interventions on these physiological variables (Barker and Armstrong, 2011; Winter et al., 2006).

The results of reliability studies conducted on moderately- and well-trained adult distance runners generally show a good-level of reproducibility (TE <5%) for variables relating to $\dot{V}O_2$ (Brisswalter and Legros, 1994; Midgley et al., 2007b; Pereira and Freedson, 1997). Oxygen cost used as a measure of RE, has a day-to-day TE of 2.4-4.7% despite showing pronounced inter-individuals differences in well-trained runners (Brisswalter and Legros, 1994; Morgan et al., 1991; Saunders et al., 2004b). Quantification of RE using the energy cost method takes account of the RER value, thus recognising that the energy expended for any given sub-maximal running speed is influenced by both $\dot{V}O_2$ and substrate utilisation (Fletcher et al., 2009). It has therefore been suggested that energy cost may provide a more valid (Shaw et al., 2014) and reliable (Shaw et al., 2013) measure than oxygen cost for RE, however the reproducibility of this parameter is largely untested. In addition, current guidelines suggest a test-retest TE of ~10% should be expected for measurements of BL at any given speed or work rate (Winter et al., 2006), and HR will fluctuate 2-8 beats$\cdot$min^{-1} for the same intensity on different days (Achten and Jeukendrup, 2003; Lambert et al., 1998). It is currently unknown whether test-retest reliability is similar for physiological parameters in junior distance runners.

High intra-class correlation coefficient (ICC) values (r=0.81-0.97) have previously been reported for $\dot{V}O_{2max}$ scores obtained during test-retest scenarios in children (Paterson et al., 1981; Pivarnik et al., 1996) and trained adolescents (Rivera-Brown and Frontera, 1998; Rivera-Brown et al., 1995), however these studies used outdated and questionable methods to scale for differences in body mass and define attainment of $\dot{V}O_{2peak}$/$\dot{V}O_{2max}$ in participants. Utilising allometrically adjusted values to determine $\dot{V}O_{2max}$ and RE for the population under investigation is likely to provide a more valid and accurate assessment of reliability in these measures.

2.3.2 Speed and Biomechanical Measurements

To evaluate the efficacy of a ST intervention, a number of testing protocols have been recommended to measure force-related capabilities (Faigenbaum et al., 2003; Jaric, 2002; Lloyd et al., 2014). For non-strength trained individuals, such as adolescents, an isometric assessment of strength is preferred to a dynamic 1RM test for reasons relating to time efficiency, task complexity, and safety (Faigenbaum et al., 2003; Lloyd et al., 2014). The isometric quarter-squat is widely used as a valid means of assessing lower-limb MVC (McMaster et al., 2014). A previous study found the isometric half-squat produced excellent reliability (ICC: 0.95) in healthy male adults (Blazevich et al., 2002) and the isometric mid-thigh pull test has also shown high reliability (ICC 0.92) for peak force values in resistance-trained participants (De Witt et al., 2018). However, it appears that no studies have been conducted which have examined the reliability of an isometric quarter-squat in adolescents.

Studies have reported excellent inter-day reliability for SJ height (ICC: 0.94) and CMJ height (ICC: 0.95) in children (Fernandez-Santos et al., 2015), and 10-40 m sprint (ICC: 0.88-0.98, TE: 0.8-2.1%) in 8-18 year olds (Rumpf et al., 2011). High levels of reliability (ICC: 0.97-0.99) have also been shown for 10-yard (Mann et al., 2016) and 40-yard (Mann et al., 2015) sprint time in Collegiate male football players (20 years old). Similarly, excellent reliability has been reported in adolescent rugby players (14-17 years) for 10 m (ICC: 0.95, TE: 1.8%), 20 m (ICC: 0.97, TE: 1.3%) and 40 m (ICC:

0.97, TE: 1.2%) sprints from a standing start (Gabbett et al., 2008). There is currently no literature which has specifically assessed the variability of these measures in a group of young distance runners. Normalisation of strength-related metrics to body size using allometric scaling is recommended (Folland et al., 2008a; Jaric, 2002). However, this is rarely performed within the literature on adolescent distance runners (Cole et al., 2006; Dellagrana et al., 2015; Mikkola et al., 2007) and may have influenced the conclusions which were drawn in these studies (Crewther et al., 2009).

5.1.3 Study Aims

Prior to conducting an experiment, it is important to quantify the error associated with measurements. RE, sFBLC and s$\dot{V}O_{2max}$ have all been shown to be important determinants of performance in adolescent distance runners (Almarwaey et al., 2003), however reliability of these measures remains unreported in this population. Valid assessments of MVC, RFD and maximal sprint speed are also important tools to evaluate the impact of a ST intervention, but reliability has previously not been quantified in post-pubertal distance runners. Previous studies have also tended to measure the reliability of various parameters independently, and no studies have reported the repeatability of a number of measures in the same group of athletes. It is also necessary to apply a population-specific scaling exponent when quantifying measures that are influenced by body size, recognising that the standard ratio method for partitioning body mass holds less validity. Thus, the purpose of this study was to compare the inter-session reliability of a number of physiological and biomechanical parameters in a group of competitive adolescent distance runners following a process of allometric scaling.

5.2 Methods

To address the aims of this study, two discrete investigations were conducted using different groups of participants. Methods will therefore be reported separately for physiological measurements, and maximal speed and biomechanical variables.

5.2.1 Physiological Measurements

5.2.1.1 Study Design

This study adopted a test-retest design whereby participants were required to attend the physiology laboratory for two identical trials separated by 3-7 days.

5.2.1.2 Participants

Sixteen (8 male, 8 female) high-performing young distance runners participated in the test-retest part of this study. All participants had previously run on a motorised treadmill, possessed at least two years of competitive racing experience and were of national (*n*=12) or international standard (*n*=4) in their age-group. To calculate an appropriate power function for $\dot{V}O_2$ and $\dot{V}O_{2max}$ to scale participants for differences in body size, data were pooled with a larger group (*n*=42) of young distance runners. Characteristics of the participants are shown in Table 5.1.

Table 5.1. Descriptive characteristics of male (M) and female (F) study participants (data are mean ± standard deviation). $\dot{V}O_{2max}$ = maximal oxygen uptake, sLTP = speed at lactate turnpoint

Measure	Test-retest cohort		Scaling cohort	
	M (*n*=8)	F (*n*=8)	M (*n*=20)	F (*n*=22)
Age (y)	16.3 ± 1.2	17.0 ± 1.5	17.0 ± 1.4	17.1 ± 1.2
Stature (cm)	176.6 ± 3.4	169.5 ± 6.3	176.9 ± 5.7	168.5 ± 6.1
Body mass (kg)	59.8 ± 7.1	51.8 ± 7.0	62.1 ± 6.6	52.7 ± 5.8
Sum of skinfolds (mm)	23.1 ± 4.2	38.6 ± 16.5	24.4 ± 4.2	38.2 ± 13.5
$\dot{V}O_{2max}$ ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	73.3 ± 4.2	64.3 ± 5.8	69.9 ± 8.3	60.4 ± 6.3
sLTP ($km{\cdot}h^{-1}$)	16.0 ± 1.1	14.5 ± 0.5	16.0 ± 1.4	14.1 ± 1.2

5.2.1.3 Procedure

Each trial involved anthropometric measurements followed by the sub-maximal and maximal treadmill running tests. Protocols are described in Section 3.5.

5.2.1.4 Measurements

Measurements are reported in accordance with the descriptions provided in Section 3.6. For comparative purposes, RE was expressed as both oxygen cost and energy cost of running.

5.2.2 Speed and Biomechanical Measurements

5.2.2.1 Study Design

Participants were required to attend three testing sessions, each separated by 2-5 days. The first session involved familiarisation with the testing procedures (see Section 3.7). Data collected during the second and third testing sessions was used for subsequent analysis of inter-day (test-retest) reliability.

5.2.2.2 Participants

Twelve (6 male, 6 female, 17.8 ±1.4 years, 59.7 ±7.5 kg) competitive junior distance runners participated in the reliability aspect of this study. These participants were grouped with a larger cohort of adolescent runners of a similar competitive standard (15 male, 18 female, 17.4 ±1.3 years, 58.5 ±6.8 kg) to obtain appropriate allometric scaling exponents for this population.

5.2.2.3 Procedure and Measurements

Data were conducted as per the descriptions provided in Section 3.7.

5.2.3 Allometric Scaling

To account for differences in body mass between individuals, a ratiometric index has been favoured in similar studies to those included in this thesis, for scaling parameters relating to $\dot{V}O_2$ and strength-related variables (Barnes et al., 2015; Cole et al., 2006; Dellagrana et al., 2015; Mikkola et al., 2007; Wong et al., 2010). This scaling approach is only valid if the relationship between body mass and a physiological variable are directly proportional, which is rarely the case (Atkinson and Batterham, 2012; Curran-Everett, 2013). To account for the confounding influence of body size, power laws have been suggested based upon the mathematical principles of allometry (Welsman and Armstrong, 1996). There is however little agreement as to the most appropriate scaling exponent to employ for homogenous groups of individuals such as high-performing adolescent athletes (Lolli et al., 2017).

5.2.3.1 Scaling Procedure

To calculate appropriate exponents for variables requiring expression relative to body size in the current cohort, body mass data from the larger groups was first linearised via natural log transformation and homogeneity of regression was compared for males and females for each dependent variable via an analysis of covariance (ANCOVA). Results of the ANCOVA tests revealed that the slopes of the log/log transformations did not differ for males and females. Relationships between log-transformed body mass and log-transformed absolute values for each dependent variable were first determined using a Pearson's correlation test to confirm whether body mass was indeed an influencing factor. Where a significant relationship existed between body mass and the dependent variable, a common power function for males and females was calculated via linear regression on the logarithmic transformation of each data set by the formula $ln_y = ln_a + b.ln_x$ and used for both groups when scaling each variable. Antilogarithms of the adjusted means from the ANCOVA were divided by the antilogarithm of the mean body mass for all participants included in the analysis raised to the allometric exponent to obtain the mean power function ratio standard for males and females. To assess the extent of a residual size correlation, linear regression analysis was performed between body mass values and each physiological variable normalised by the scaling exponent. For exponents to be accurate, the R^2 value should approach zero, indicating that any differences observed in the physiological variable are independent of body mass.

5.2.4 Statistical Analyses

For the large cohorts used for scaling purposes and the test-retest cohorts used in reliability analysis, the normality of the distributions was assessed using a Shapiro-Wilks test and visually inspected using Q-Q plots. The homogeneity of the variance was assessed using Levene's test. All variables were found to be normally distributed (p>0.05) and satisfied the assumption of homoscedasticity.

To determine whether a systematic bias was present between trial 1 and trial 2, a two-factor (sex x trial) analysis of variance (ANOVA) with repeated measures was performed. Effect sizes were also calculated as the absolute change in the mean scores between trials divided by the pooled SD from both trials. The TE value provided an absolute index of reliability that encapsulates both the random and systematic error associated with a measurement (Batterham and George, 2003), and was calculated as the SD of the difference between trial 1 and trial 2 divided by $\sqrt{2}$. MDC_{95} values were also calculated as described in Section 3.8. Two-way random (single measure) ICC's were also calculated as an indicator of the relative consistency for each measure (Weir, 2005) including a 95%CI.

5.3 Results

5.3.1 Allometric Scaling Exponents

Statistically significant relationships (r=0.68-0.81, p<0.001) were found between log-transformed body mass and log-transformed absolute values for $\dot{V}O_{2max}$, $\dot{V}O_2$ (across all three speeds), MVC and $vGRF_{jump}$. Peak RFD on the squat jump showed no relationship with body mass (r=0.03, p=0.870), therefore this variable was not scaled to account for differences in body mass between participants. The characteristics of the participants used to calculate scaling exponents for whole body mass are shown in Table 5.2 and Table 5.3. No significant differences were found between scaling exponents for males and females across $\dot{V}O_2$ or kinetic parameters. Log-linear regression revealed scaling exponents which approximated two-thirds for $\dot{V}O_{2max}$ and $\dot{V}O_2$ in males and females. When scaling exponents were applied, a very weak relationship was present between body mass and each dependent variable ($R^2<0.17$, $p>0.05$).

Table 5.2a. Characteristics of male participants and scaling exponents for sub-maximal oxygen uptake ($\dot{V}O_2$) and maximal oxygen uptake ($\dot{V}O_{2max}$). sLTP = speed at lactate turnpoint

Parameter (y)	***n***	**Age (years)**	**Mass (x) (kg)**	**Mean ±SD (L·min^{-1})**	$\boldsymbol{y = ax^b}$ **(ml·min^{-1})**
$\dot{V}O_{2max}$	20	17.0 ± 1.4	62.1 ± 6.6	4.322 ± 0.577	$286.5\ x^{0.66}$
$\dot{V}O_2$ at:					
sLTP	19	17.0 ± 1.4	61.8 ± 6.7	3.726 ± 0.456	$243.4\ x^{0.66}$
sLTP -1 km·h^{-1}	20	17.0 ± 1.4	62.1 ± 6.6	3.515 ± 0.411	$247.7\ x^{0.64}$
sLTP -2 km·h^{-1}	15	17.1 ± 1.3	61.7 ± 6.7	3.377 ± 0.368	$212.0\ x^{0.67}$

Table 5.2b. Characteristics of female participants and scaling exponents for sub-maximal oxygen uptake ($\dot{V}O_2$) and maximal oxygen uptake ($\dot{V}O_{2max}$). sLTP = speed at lactate turnpoint

Parameter (y)	***n***	**Age (years)**	**Mass (x) (kg)**	**Mean ±SD (L·min^{-1})**	$\boldsymbol{y = ax^b}$ **(ml·min^{-1})**
$\dot{V}O_{2max}$	20	17.2 ± 1.3	53.0 ± 5.9	3.224 ± 0.417	$237.6\ x^{0.66}$
$\dot{V}O_2$ at:					
sLTP	19	17.2 ± 1.2	53.0 ± 5.9	2.803 ± 0.312	$202.9\ x^{0.66}$
sLTP -1 km·h^{-1}	21	17.1 ± 1.2	52.4 ± 5.8	2.623 ± 0.274	$206.5\ x^{0.64}$
sLTP -2 km·h^{-1}	22	17.1 ± 1.2	52.7 ± 5.8	2.462 ± 0.241	$172.5\ x^{0.67}$

Table 5.3. Scaling exponents for kinetic variables in male (17.2 ±1.5 years; 63.7 ±5.4 kg) and female participants (17.5 ±1.1 years; 54.1 ±4.5 kg). SD = standard deviation, MVC = maximal voluntary contraction, $vGRF_{jump}$ = vertical ground reaction force during squat jump

	Male (*n*=15)		**Female (*n*=18)**	
Parameter (y)	**Mean ±SD**	$\boldsymbol{y = ax^b}$	**Mean ±SD (N)**	$\boldsymbol{y = ax^b}$ **(N)**
Isometric quarter squat MVC	2314 ± 263	$188.1\ x^{0.61}$	1749 ± 267	$156.1\ x^{0.61}$
Squat jump $vGRF_{jump}$	1439 ± 149	$64.1\ x^{0.76}$	1230 ±161	$61.8\ x^{0.76}$

5.3.2 Physiological Results

5.3.2.1 Plateaus in expired gases

The MDC values for $\dot{V}O_2$ in the final 60 s of each submaximal stage across both trials were <122 mL·min^{-1}. Values for $\dot{V}CO_2$ were of a similar magnitude (98-113 mL·min^{-1}). Of the 174 samples analysed for the larger cohort (*n*=42), 11 $\dot{V}O_2$ samples and ten $\dot{V}CO_2$ samples failed to meet steady-state criteria.

All participants with the exception of three (two from the test-retest cohort and one from the larger sample) achieved the criteria for a plateau in $\dot{V}O_2$ at maximum. For the participants who achieved a plateau, at least two of the three traditional criteria for achievement of $\dot{V}O_{2max}$ were also met (RER ≥ 1.1, HR ≥ 95% of age-predicted maximum, end BL ≥ 8 mMol·L^{-1}). The samples that failed to demonstrate a plateau in gas exchange (for $\dot{V}O_2$, $\dot{V}CO_2$ or $\dot{V}O_{2max}$) were excluded from subsequent analysis. Revised participant numbers used to generate scaling exponents and reliability statistics are shown within each table.

5.3.2.2 Reliability

Body mass displayed high consistency between trials (mean difference: 0.4±0.3 kg, TE: 0.34%). Although sFBLC demonstrated high reliability between trials (Table 5.4), variability of this measure across all speeds was far higher (mean difference: 0.2±0.2 mMol·L^{-1}, 95% CI: 0.1-0.2 mMol·L^{-1} TE: 6.2%). HR at FBLC was also highly reliable (Table 5.4) and displayed similar consistency across all speeds for each participant (mean difference: 4±4 beats·min^{-1}, 95% CI: 4-5 beats·min^{-1}, TE: 1.6%). RPE tended to display lower reliability at slower relative speeds. At sLTP -2 km·h^{-1}, a significant difference (F=17.0, p=0.001) was detected between trials (mean difference: 1±0.8, TE: 4.9%, ES: 1.03, ICC: 0.36), whereas RPE at sLTP showed good reliability (mean difference: 0.6±0.5, TE: 2.4%, ES: 0.56, ICC: 0.79).

Results of ANOVA tests for all other parameters, with the exception of end BL (F=4.76, p=0.047), showed no systematic bias between trial 1 and trial 2 across any parameter (p>0.05). Similarly, ES for test-retest differences across all measures were small (<0.6) or trivial (<0.2). Within-subject variability for $\dot{V}CO_2$ was low across assessed speeds (TE: 1.2-1.4%). As shown in Table 5.4, parameters relying on measurement of $\dot{V}O_2$ and $\dot{V}CO_2$ all demonstrated a high degree of reliability between trials (ICC: 0.82-0.98, TE: 1-2%), however it is notable that measures of energy cost produced lower TE values than oxygen cost at the same speeds. The MDC values are also shown in Table 5.4. When expressed as a percentage, MDC for energy cost was lower than oxygen cost for each speed.

5.3.3 Speed and Biomechanical Results

5.3.3.1 Reliability

Table 5.5 presents the reliability statistics for maximal speed and kinetic measures associated with the isometric quarter squat and squat jump tests. ANOVA values indicated that there were no statistically significant differences between trials for any of the variables (p>0.05). The 20 m sprint and squat jump displacement displayed acceptable levels of reliability (TE: <5%, ICC: >0.9, ES: ≤0.27), however MVC (TE: 5.1%, ICC: 0.65, ES: 0.62), $vGRF_{jump}$ (TE: 5.7%, ICC: 0.49, ES: 0.79) and peak RFD (TE: 11.2%, ICC: 0.54, ES: 0.78) exhibited far lower levels of measurement consistency.

Table 5.4. Test-retest reliability of physiological variables during maximal and submaximal test. * indicates significant difference ($p<0.05$) compared to trial 1.

ES = effect size, FBLC = fixed blood lactate concentration, HR = heart rate, ICC = intra-class correlation coefficient, MDC_{95} = 95% confidence interval for minimal detectable change, RPE = rating of perceived exertion (6-20 scale), sLTP = speed at lactate turnpoint, s$\dot{V}O_{2max}$ = speed associated with maximal oxygen uptake, TE = typical error, $\dot{V}O_{2max}$ = maximal oxygen uptake

Parameter	***n***	**Trial 1**	**Trial 2**	**ES**	**Interpretation**	**TE**	**TE (%)**	**ICC (95% CI)**	**MDC_{95}**	**MDC (%)**
Maximal running										
$\dot{V}O_{2max}$ ($ml{\cdot}kg^{-0.67}{\cdot}min^{-1}$)	14	267.2 ± 32.5	268.2 ± 29.8	0.17	Trivial	2.72	1.02	0.98 (0.94 – 0.99)	7.5	2.8
($L{\cdot}min^{-1}$)		(3.90 ± 0.80)	(3.90 ± 0.79)							
s$\dot{V}O_{2max}$ ($km{\cdot}h^{-1}$)	14	18.6 ± 1.5	18.6 ± 1.1	0.49	Small	0.34	1.83	0.82 (0.52 – 0.94)	0.9	5.1
Time to exhaustion (s)	16	382 ± 73	371 ± 69	0.30	Small	13.7	3.64	0.92 (0.79 – 0.97)	38.0	10.1
End lactate ($mMol{\cdot}L^{-1}$)	16	9.6 ± 1.8	9.0 ± 2.0*	0.51	Small	0.6	6.36	0.79 (0.47 – 0.92)	1.6	17.6
Oxygen cost ($ml{\cdot}kg^{-0.67}{\cdot}km^{-1}$), absolute values are shown in brackets ($L{\cdot}km^{-1}$)										
sLTP	15	889.6 ± 77.0 (13.1 ± 2.2)	891.4 ± 71.2 (13.0 ± 2.1)	0.39	Small	16.1	1.81	0.88 (0.68 – 0.96)	44.7	5.0
sLTP-1 $km{\cdot}h^{-1}$	16	894.5 ± 74.4 (13.1 ± 2.2)	886.9 ± 69.2 (13.0 ± 2.1)	0.38	Small	18.3	1.45	0.90 (0.75 – 0.96)	35.9	4.0
sLTP-2 $km{\cdot}h^{-1}$	14	896.7 ± 85.3 (13.1 ± 2.4)	881.3 ± 68.8 (13.0 ± 2.1)	0.37	Small	17.8	2.00	0.89 (0.68 – 0.96)	49.2	5.5
Energy cost ($kJ{\cdot}kg^{-0.67}{\cdot}km^{-1}$), absolute values are shown in brackets ($kJ{\cdot}km^{-1}$)										
sLTP	13	19.3 ± 1.7 (287.0 ± 50.2)	19.5 ± 1.5 (284.7 ± 47.4)	0.33	Small	0.233	1.20	0.93 (0.79 – 0.98)	0.6	3.3
sLTP-1 $km{\cdot}h^{-1}$	16	19.2 ± 1.6 (281.3 ± 48.4)	19.0 ± 1.5 (278.7 ± 45.7)	0.34	Small	0.267	1.40	0.92 (0.78 – 0.97)	0.7	3.9
sLTP-2 $km{\cdot}h^{-1}$	13	19.1 ± 1.8 (278.0 ± 52.2)	18.8 ± 1.5 (276.9 ± 47.5)	0.28	Small	0.305	1.61	0.93 (0.79 – 0.98)	0.8	4.5

Speed at FBLC ($km \cdot h^{-1}$)										
2 $mMol \cdot L^{-1}$	16	14.5 ± 1.4	14.6 ± 1.4	0.12	Trivial	0.14	0.94	0.99 (0.97 – 1.00)	0.4	2.7
3 $mMol \cdot L^{-1}$	16	15.5 ± 1.3	15.6 ± 1.3	0.09	Trivial	0.11	0.71	0.99 (0.97 – 1.00)	0.3	2.0
4 $mMol \cdot L^{-1}$	13	16.3 ± 1.3	16.4 ± 1.2	0.11	Trivial	0.12	0.76	0.98 (0.93 – 0.99)	0.3	2.0
HR at FBLC ($b \cdot min^{-1}$)										
2 $mMol \cdot L^{-1}$	16	179 ± 11	178 ± 11	0.41	Small	2.77	1.55	0.86 (0.65 – 0.95)	8	4.3
3 $mMol \cdot L^{-1}$	16	186 ± 11	185 ± 11	0.34	Small	1.87	1.01	0.92 (0.78 – 0.97)	5	2.8
4 $mMol \cdot L^{-1}$	13	189 ± 9	187 ± 10	0.37	Small	1.81	0.96	0.90 (0.70 – 0.97)	5	2.7
RPE (6-20)										
sLTP	16	15.1 ± 1.0	14.8 ± 1.2	0.56	Small	0.36	2.42	0.79 (0.49 – 0.92)	1	6.7
sLTP-1 $km \cdot h^{-1}$	16	13.8 ± 1.0	13.3 ± 1.7	0.87	Moderate	0.48	3.55	0.47 (0.03 – 0.77)	2	9.9
sLTP-2 $km \cdot h^{-1}$	16	12.6 ± 1.1	11.5 ± 1.0*	1.03	Moderate	0.59	4.90	0.36 (-0.10 – 0.71)	2	13.6

Table 5.4 (continued)

Table 5.5. Test-retest reliability of maximal speed and kinetic variables during strength tests.

ES = effect size, ICC = intra-class correlation coefficient, MDC_{95} = 95% confidence interval for minimal detectable change, MVC = maximum voluntary contraction, RFD = rate of force development, TE = typical error, $vGRF_{jump}$ = vertical ground reaction force during squat jump

Parameter	Trial 1	Trial 2	ES	Interpretation	TE	TE (%)	ICC (95% CI)	MDC_{95}	MDC (%)
20 m maximal sprint (s)	2.71 ± 0.29	2.70 ± 0.29	0.12	Trivial	0.01	0.34	0.99 (0.97 – 1)	0.03	1.0
Isometric quarter squat, absolute values are shown in brackets (N)									
MVC ($N{\cdot}kg^{-0.61}$)	166.0 ± 22.5 (2013 ± 340)	170.0 ± 20.9 (2070 ± 381)	0.62	Moderate	8.56	5.10	0.65 (0.16 – 0.89)	23.74	14.1
Squat jump, absolute values are shown in brackets (N)									
$vGRF_{jump}$ ($N{\cdot}kg^{-0.76}$)	62.1 ± 77.0 (1390 ± 203)	65.2 ± 71.2 (1462 ± 254)	0.79	Moderate	3.64	5.71	0.49 (0.03 – 0.82)	10.08	15.8
Peak RFD ($N{\cdot}s^{-1}$)	11,372 ± 3260	12,067 ± 3003	0.78	Moderate	1317	11.2	0.54 (0 – 0.84)	3650	31.1
Displacement (m)	0.251 ± 0.067	0.255 ± 0.072	0.27	Small	1.24	4.89	0.94 (0.80 – 0.98)	0.034	13.5

5.4 Discussion

This investigation aimed to establish the reproducibility of a number of physiological and biomechanical variables in a group of high-performing junior distance runners. The results provide evidence that the majority of physiological parameters can be measured with a high-degree of reliability in this population, and this is the first study to present reliability data in young athletes for $\dot{V}O_{2max}$ and RE following use of an appropriate allometric scaling exponent. In the assessment of RE, energy cost appears to be more reliable than using oxygen cost values, so should be the preferred measure for the practitioner. Other than maximal speed, kinetic variables associated with an isometric quarter-squat and a squat jump displayed moderate reliability, therefore the use of these testing methods with young non-strength trained groups requires caution.

The MDC_{95} uses the TE associated with measurement consistency and the z-score from a 95% CI. The MDC values for each variable (see Tables 5.4 and 5.5) can be utilised to determine whether a 'real' change has been observed following an intervention in high-performing junior distance runners.

5.4.1 Physiological Variables

Regardless of whether $\dot{V}O_{2max}$ or $\dot{V}O_{2peak}$ has been used to define the highest $\dot{V}O_2$ achieved, previous studies have found a high test-retest reliability (ICC=0.74-0.97) in adolescent populations (Paterson et al., 1981; Pivarnik et al., 1996; Rivera-Brown and Frontera, 1998; Rivera-Brown et al., 1995), which is in agreement with findings from this study (ICC: 0.98). This is the first study in young athletes to assess reliability of $\dot{V}O_{2max}$ following appropriate scaling for differences in the body mass within the cohort. We also applied a more stringent criteria (Midgley et al., 2009) to identify $\dot{V}O_{2max}$, than the traditional criterion (Taylor et al., 1955) that has been applied in previous studies, and excluded any participants from analysis who failed to achieve a true plateau. These two factors are likely to explain, in-part, the high ICC value observed in this study.

Oxygen cost is an important determinant of distance running performance and reliability indices in the present study (ICC: 0.88-0.90, TE: 1.81-2.00%) are similar to those reported elsewhere for well-trained (1.3%), highly trained (1.8%) and elite (2.4%) endurance runners (Morgan et al., 1991; Pereira and Freedson, 1997; Saunders et al., 2004b). The between-day stability of oxygen cost has previously been quantified in six year old children (Keefer et al., 2000), however this is the first study to show high-levels of between-test reliability in adolescent runners who are engaged in intensive training regimens. Training status appears to be an important influence in the degree of variability observed in RE (Brisswalter and Legros, 1994). The mean age of the participants in this study was <18 years, however they were all of national or international standard in their age-groups and ratio-scaled $\dot{V}O_{2max}$ scores were similar to those attained by highly-trained adult runners (male: 73.3±4.2, female: 64.3±5.8 $mL \cdot kg^{-1} \cdot min^{-1}$). Therefore despite the young age of the participants, results suggest a high level of stability in oxygen cost of running exists, which in-part may be due to the training status of these athletes.

The measure of energy cost provides a potentially more robust measure of RE, mitigating against the potentially confounding influence of substrate utilisation when dietary and lifestyle factors are not controlled adequately. Similar between-test reliability has previously been shown for oxygen cost (TE: 2.7-3.3%) and energy cost (TE: 3.1-3.7%) in trained runners (Shaw et al., 2013). This is somewhat different to the findings of this study, which showed energy cost to be more reproducible than oxygen cost across all three speeds assessed. Reliable measurement of energy cost requires $\dot{V}O_2$ and $\dot{V}CO_2$ to be consistent, as RER is derived using both values. It is likely that differences in within-subject variability for $\dot{V}CO_2$ explain the discrepancy between this study and those of Shaw and colleagues (2013), who reported much higher TE (<5.94%) than the variability we measured (1.16-1.37%). As a consequence, this meant that the RER was also more stable in the present study (TE: <4.35% vs <2.02%). Although the male participants in both studies possessed similar $\dot{V}O_{2max}$ values (75.5±5.2 vs 73.3±4.2 $mL \cdot kg^{-1} \cdot min^{-1}$), it may also be possible that the junior runners in this investigation employed lower volume training regimens than the senior runners used in the Shaw et al. (2013) study, therefore we speculate that this would reduce the daily variability in substrate metabolism and thus measures of energy cost.

s$\dot{V}O_{2max}$, which combines both RE and $\dot{V}O_{2max}$ into a single variable, has been shown to explain differences in performance that other determinants cannot (Billat and Koralsztein, 1996). Previous work has shown low TE values (2.3%) for amateur male runners with near identical s$\dot{V}O_{2max}$ values (18.6 $km \cdot h^{-1}$) to those observed in the present study (LourenÇo et al., 2011). Given that s$\dot{V}O_{2max}$ was estimated from the linear regression equation based upon $\dot{V}O_{2max}$ the speed-$\dot{V}O_2$ relationship, which has high reliability at three speeds, it is unsurprising that this parameter demonstrate high reproducibility using this protocol (ICC: 0.82, TE: 1.83%).

BL measurement during sub-maximal exercise in athletes is commonplace for monitoring and evaluation purposes. Previous studies have shown reliability coefficients of 0.92-0.95 for velocity at 4 $mMol \cdot L^{-1}$ and 0.81-0.93 for HR at 4 $mMol \cdot L^{-1}$ in moderately fit (Grant et al., 2002) and trained runners (Heitkamp et al., 1991; Weltman et al., 1990). It should be noted that the correlation coefficients used in these studies only describe the relationship between test and retest values. The ICC is a univariate statistic and provides a more robust means of determining agreement between two independent measurements. The reliability values for speed at 2-4 $mMol \cdot L^{-1}$ in the present study are also similar to those observed in a previous study on endurance-trained males, which used three trials and an ICC statistic (Pfitzinger and Freedson, 1998). The present study did however observe a far larger variability for BL measurement across absolute sub-maximal speeds (mean difference: 0.18±0.20 $mMol \cdot L^{-1}$, 95% CI: 0.14-0.22 $mMol \cdot L^{-1}$, TE: 6.24%), therefore when interpreting within-subject changes in lactate response to sub-maximal running, sFBLC should be the preferred marker for assessing change. Similarly, a significant difference ($F=4.76$, $p=0.047$) was detected between trials for BL at the end of the maximal test with moderate levels of reliability (TE: 6.36%, ICC: 0.79). Practitioners should therefore be cautious when interpreting absolute changes in BL response, particularly following a maximal bout of exercise.

Monitoring of submaximal HR provides athletes and practitioners with a low cost and non-invasive tool to assess changes in training status and may provide an indication of overtraining (Achten and Jeukendrup, 2003; Lambert et al., 1998). Under controlled conditions, HR has shown daily variability of 5-8 $beats \cdot min^{-1}$ at sub-maximal running speeds in physically active adults (Lamberts et al., 2004). The variability across all speeds in the present study is slightly lower (mean difference: 4±4 $beats \cdot min^{-1}$, 95% CI: 3.7-5.2 $beats \cdot min^{-1}$, TE: 1.60%). However, the data supports the recommendation that caution should be observed when interpreting subtle changes in HR at absolute running speeds, as a difference of <6 $beats \cdot min^{-1}$ can be attributed to normal variability (Achten and Jeukendrup, 2003). The reproducibility of HR at FBLC (ICC: 0.86-0.92, TE: 0.96-1.55%) was higher than values found in other studies using recreational runners (ICC: 0.47-0.79, TE: 1.6-4.3%), which have used HR at intensities corresponding to fixed physiological thresholds (LourenÇo et al., 2011; Peserico et al., 2015). Despite the age of the participants used in this study, this discrepancy is likely due to the training status of the athletes, as similar dietary and lifestyle constraints were applied, and previous work has shown lesser-trained runners show larger daily variability in HR scores (Heitkamp et al., 1991) compared to well-trained runners (Brisswalter and Legros, 1994).

Borg's 6-20 RPE scale is a tool widely used by physiologists and coaches to subjectively assess physical stress (Borg, 1982; Eston et al., 1987). The scale has been validated for running-based exercise against HR, BL and $\dot{V}O_2$ (Ekblom and Golobarg, 1971; Robertson, 1982) and is typically assumed to possess a high level of reliability (Skinner et al., 1973; Stamford, 1976; Wenos et al., 1996). However, the reliability statistic applied in these papers were correlation coefficients, which only evaluates the degree of association and does not assess the level of agreement between repeat tests. More recent work has cast doubt over the repeatability of the RPE scale during incremental exercise (Grant et al., 2002; Lamb et al., 1999) using ICC's and the 95% limits of agreement analysis method. Similar to the findings of this study, Lamb and colleagues (1999) observed a statistically significant difference ($p<0.05$) between trials at the lowest of four intensities they assessed and a similar mean difference (0.9 vs 1.1). Interestingly, the reliability of RPE improved as intensity of exercise increased, which is similar to the finding of Grant and associates (2002) who measured RPE at the speed associated with LT and speed at 4 $mMol \cdot L^{-1}$. It has been suggested that the reliability of RPE improves over several trials (Eston and Williams, 1988), indicating that, for lower intensities (LTP -2 $km \cdot h^{-1}$) at least, it may be necessary to include familiarisation sessions with adolescent athletes to ensure the RPE provided is reliable.

Time of day, footwear and environmental conditions were controlled for in the present study, but dietary and training constraints were not strictly enforced. In an attempt to control for these potentially confounding issues, most participants trials were separated by seven days. From personal communication with parents (and participants), this period represented a typical microcycle of training for these runners. It is therefore likely that a highly similar pattern of training and lifestyle activities preceded each trial. Requests for consistency in lifestyle and diet in the 48 h prior to trials were also enforced by parents/guardians who were present for most of the testing sessions. Familiarity with the speeds used to assess RE and adequate control of confounding factors are therefore likely to have contributed towards the low within-subject variability observed for physiological measures in this study.

5.4.2 Speed and Biomechanical Variables

In contrast to the majority of physiological parameters, the reliability of several biomechanical variables is questionable. The kinetic variables associated with the isometric quarter squat (MVC) and squat jump ($vGRF_{jump}$ and peak RFD) showed moderate reliability (ICC: 0.49-0.65, TE: >5%), whereas maximal speed and squat jump displacement both showed excellent reliability (ICC: >0.9, TE: <5%).

The high level of reliability observed for the 20 m sprint test (TE: 0.34%, ICC: 0.99, ES: 0.12) is in agreement with other works that have used measures of linear speed in children and adolescents (Gabbett et al., 2008; Rumpf et al., 2011). The MDC_{95} value indicates that a 0.03 s (1.0%) improvement following an intervention would provide 95% certainty the change in maximal speed is genuine. A previous review found that 6-13 weeks of combined ST and SpT improved short sprint (0-30 m) times by -5.8% (ES: -1.3) in post-pubertal males (14.7 years), and ST alone enhanced performance by -1.5% (ES: -0.3) (Rumpf et al., 2012). The majority of studies reviewed utilised standing starts to assess sprint time, however one study registered a 10.9% (ES: -1.75) improvement for a flying sprint (5 m) in adolescent soccer players (17 years) following an eight week HRT intervention (Chelly et al., 2009). It is therefore proposed that a 20 m maximal sprint test will be a reliable and sensitive means of assessing changes in top speed running following a training intervention in a group of adolescent distance runners.

The temporal reproducibility for squat jump height is also acceptable (TE: 4.89%, ICC: 0.94, ES: 0.27) and the same as values observed for 6-12 year old children (Fernandez-Santos et al., 2015). Moreover, similar reliability (ICC: 0.93) has been recorded in 13 year old swimmers (Papadopoulos et al., 2000) and a group of physically active male youths (13.5 years) (Lloyd et al., 2009). The vertical displacement an individual achieves during a squat jump is directly proportional to the impulse generated under the force-time curve, once body weight has been accounted for. The same amount of impulse can be generated in a number of ways, which results in different force-time profiles that may explain the inter-trial discrepancies in the kinetic variables measured during the squat jump.

The $vGRF_{jump}$ displayed a low ICC value (0.49), which is in contrast to previous investigations, in resistance-trained participants (ICC: 0.99) (Chiu et al., 2004) and physically-active men (ICC: 0.97) (McLellan et al., 2011). The ICC statistic represents the proportion of variance in a data set that can be attributed to error (Weir, 2005), however this is sensitive to the range of values contained within a sample and does not account for systematic bias. Therefore an interpretation of TE is also recommended (Atkinson and Nevill, 1998). Over half (51%) of the observed score variance for $vGRF_{jump}$ is due to error, however the TE value (5.71%) indicates that participants were relatively consistent in their scores between the two trials. Moreover, although a moderate ES (0.78) was identified between trials, a statistically significant difference was not identified (F=2.03, p=0.185). The between-participant coefficient of variation was also substantially lower (6.8% vs 14.9% vs 39.0%) than the aforementioned studies (Chiu et al., 2004; McLellan et al., 2011), indicating that the range of data within the sample of the present study was small. This may have also contributed to the low ICC result observed.

Peak RFD also displayed moderate reliability (ICC: 0.54), and systematic bias was also somewhat high (TE: 11.2%), thus MDC_{95} is approximately a third of the group mean score (31.1%). Although this degree of change may appear difficult to accomplish following a short-term (8-12 weeks) training intervention, changes in excess of 31% have consistently been observed in the literature for non-strength trained individuals following exposure to 2-3 ST sessions per week (Hernández-Davó and Sabido, 2014). One study in distance-runners also found a 26% improvement in peak RFD during a loaded squat following eight weeks of HRT (Storen et al., 2008). Previous reliability studies that have included a measure of peak RFD during jump testing have shown mixed results (Chiu et al., 2004; Haff et al., 2000; McLellan et al., 2011; Moir et al., 2005). McLellan and colleagues (2011) reported low reliability (ICC: 0.89, TE: 14.8%) for peak RFD during the squat jump in a group of physically active men (23 years), which is consistent with work by Moir and associates (2005). Conversely, other works have shown excellent reliability (ICC: >0.9, TE: <5%) for peak RFD during squat jumping (Chiu et al., 2004; Haff et al., 2000).

High levels of reliability (ICC: 0.96, TE: <5%) have previously been observed for 1RM strength tests in professional youth soccer players (Dos'Santos et al., 2017), 10 year old children (Faigenbaum et al., 1998) and resistance-trained adolescent (15.9 years) males (Faigenbaum et al., 2012). Similarly, high inter-session reliability values (ICC: 0.96-0.97) were also reported for MVC (peak force) in an isometric mid-thigh pull in youth soccer players (Dos'Santos et al., 2017) and isometric half-squat in athletic males aged 19-26 years (Blazevich et al., 2002). The ICC value for MVC in the present study (0.65) is substantially lower than those identified above, however the TE appears to be similar (~5%), indicating a comparable level of systematic bias exists compared to previous investigations (Dos'Santos et al., 2017). A wide range of scores is necessary to generate a high ICC statistic, therefore the differences between studies may be partly attributable to the range of values included in the samples. The between-participant coefficient of variation for the studies authored by

Faigenbaum and colleagues (1998, 2012) was ~30% compared to 5.9% in the present investigation, suggesting that this may be a factor in the lower ICC result recorded in the present investigation.

The discrepancies observed between trials may be explained by factors relating to systematic bias, such as a learning effect or motivation, plus random variation. Random change is the consequence of normal biological variation and has a more pronounced effect in smaller sample sizes (Hopkins, 2000). Some of the observed TE could be explained by random 'noise', however it is more likely that participants experienced a learning effect across the trials as an improvement was observed for every kinetic variable (see Table 5.5). This learning response can be explained by the training status of participants, as more skilled individuals are likely to produce a higher level of movement pattern consistency. This observation is supported by the reliability results for the 20 m sprint, which in high-performing middle- and long-distance runners is likely to display greater consistency in movement execution, than the strength-tests, which were novel for all participants. Moreover, excellent inter-session reliability (ICC: 0.97) has been found for peak force during a squat jump assessment performed on a supine leg press in adolescent (11-15 years) males (Meylan et al., 2015), which demands a lower level of skill compared to a traditional standing squat jump. It also appears that studies using cohorts of resistance-trained adolescent participants generally show more reliable outcomes (Dos'Santos et al., 2017; Faigenbaum et al., 2012). The procedure employed for this study included a familiarisation trial, however it is suggested that a more extensive familiarisation phase is included for adolescent distance runners if these variables are measured by others.

5.4.3 Limitations

This study is not without limitations. The relatively small sample sizes used to quantify a suitable scaling exponent for this population may have generated imprecise estimates owing to sampling error. A recent meta-analysis on allometric scaling of $\dot{V}O_{2max}$ established exponents of 0.71 for young individuals, 0.71 for athletes and 0.70 for treadmill testing assessment (Lolli et al., 2017). These values are similar to the estimated scaling exponent calculated in the present study (b=0.67) and fall within the 95% CI for each moderator (Lolli et al., 2017), therefore any error that exists for the $\dot{V}O_2$ related measures, is likely to be minimal. Similarly, it is widely recommended that body mass should be raised to the power of two-thirds when scaling measurements of muscular force (Crewther et al., 2009; Folland et al., 2008a; Jaric, 2002; 2003; Jaric et al., 2005; McMahon, 1984), however a range (0.58-1.14) of other exponents have also been identified for various populations (Atkins, 2004; Batterham and George, 1997; Jaric, 2002; Jaric et al., 2002). The scaling factors derived in the present study (MVC: b=0.61, $vGRF_{jump}$: b=0.76) approximate the suggested exponent of 0.67, thus providing confidence that these corrections for body mass are appropriate for this cohort. These findings emphasise that traditional ratio (per kg) expressions are unsuitable and may incur error when attempting to describe changes in physiological parameters following an intervention (Atkinson and

Batterham, 2012).

The test-retest design of the present study provides practitioners with valuable insight into the reproducibility of physiological measures. However the inclusion of a third trial for both physiological and biomechanical investigations would provide a more accurate impression of the systematic error which may exist in each measure.

5.4.4 Conclusions

Practitioners and coaches can be confident that measurements of physiological parameters in junior distance runners are highly reproducible when external factors are appropriately constrained. The exception to this is RPE, particularly at low intensities of exercise. Caution should be observed when interpreting small changes in BL (<0.2 $mMol \cdot L^{-1}$) and HR (<6 $beats \cdot min^{-1}$) as part of an athlete monitoring process as it is likely this is normal variability in the criterion measure. The sFBLC appears to provide a more sensitive metric for reliably identifying a change in an athlete's physiology compared to the BL value at a given speed. Energy cost should be the preferred measure of RE as this parameter accounts for day-to-day variations in substrate utilisation and demonstrates higher reliability than traditional oxygen cost measurement. Maximal speed and squat jump displacement also display excellent day-to-day consistency. Conversely, practitioners should be wary when interpreting kinetic measures associated with maximal and dynamic strength testing, as reliability is only moderate.

5.5 Perspective

The overriding objectives of this thesis are to examine current ST habits in runners, and evaluate the acute and chronic efficacy of ST on distance running performance, with an experimental focus on the post-pubertal adolescent age-group. Prior to addressing specific aims, it is important to quantify the reproducibility of the measures intended for use in the experimental studies (Atkinson and Nevill, 2001). This is especially critical for testing protocols that will be unfamiliar to young distance runners, such as strength-related measures and RPE. If a measurement test cannot provide adequate reproducibility across repeated trials, then it cannot be considered a valid tool to assess the change which may occur as a consequence of an intervention (Batterham and George, 2003). Establishing TE of measurement also enables a MDC_{95} value to be calculated, which represents a threshold of high practical certainty that any observed change is real. The MDC_{95} can also be used alongside an observed effect to provide an MBI term, which is based upon the probability that an effect is beneficial, harmful or trivial (Deighton et al., 2017).

The misrepresentation provided by ratio-scaling physiological- and strength-variables by whole body mass has previously been highlighted (Atkinson and Batterham, 2012; Curran-Everett, 2013; Jaric, 2003; Lolli et al., 2017), but remains common in the literature. There is disagreement surrounding the most appropriate scaling exponent to use for various parameters and different populations to render an expression that is independent of the confounding influence of body mass. Therefore, it is necessary to obtain an appropriate scaling factor derived from a representative sample of the population under investigation for each specific task (Jaric et al., 2002; Lolli et al., 2017; Shaw et al., 2014). This chapter has therefore contributed to the overriding aim of this thesis by clarifying the reliability of physiological and biomechanical markers relating to performance outcomes in adolescent distance runners, following a process of allometric scaling.

The measurements selected for scrutiny in this study are based upon the detailed discussion of the main physiological- and neuromuscular-factors that underpin middle- and long-distance running performance (see Section 2.2-2.4). Despite the consensus in the literature surrounding the advantages of ST techniques for adult distance runners (Study 1, Section 2.5) and a high-proportion of engagement in junior distance runners (Study 2, Chapter 4), there is a scarcity of studies that have attempted to investigate the effects of ST on adolescent distance runners. This age-group has also been highlighted as important in terms of the timing of sport-specialisation and the necessity to participate in ST for long-term health and performance benefits (see Section 2.7). The following Chapter will therefore address this gap in the literature by studying the effects of a ten week ST intervention on post-pubertal adolescent distance runners.

Based upon the literature associated with maximising the potentiating effects of a warm-up in endurance athletes (see Section 2.6), it is proposed that the inclusion of a strength-based exercise in the warm-up of young distance runners will acutely enhance performance. The final study of this thesis (see Chapter 7) will therefore address this question by investigating the impact of performing a set of DJ prior to a physiological assessment in a group of high-performing middle-distance runners. The reliability values identified in this study will facilitate a more rigorous statistical analysis process in these two experimental studies, and enable practically meaningful conclusions to be drawn.

CHAPTER 6

EFFECTS OF STRENGTH TRAINING ON POST-PUBERTAL ADOLESCENT DISTANCE RUNNERS

(Study 4)

Published papers from this chapter:

Blagrove, R. C., Howe, L. P., Cushion, E. J., Spence, A., Howatson, G., Pedlar, C. R. and Hayes, P. R. (2018) Effects of strength training on postpubertal adolescent distance runners. *Medicine and Science in Sports and Exercise,* 50(6), pp. 1224-1232.

6.1 Introduction

Success in distance running can be attributed to a variety of physiological and biomechanical factors (Thompson, 2017). From a physiological perspective, energy acquired via aerobic means contributes a significant proportion to performance outcomes of middle- and long-distance events (Gastin, 2001). Indeed, several studies have demonstrated that aerobic qualities such as $\dot{V}O_{2max}$, s$\dot{V}O_{2max}$, RE and sub-maximal lactate values have a strong relationship with distance running performance (Deason et al., 1991; Ingham et al., 2008; Yoshida et al., 1990). These variables have also been shown to be important predictors of performance in adolescent distance runners (Almarwaey et al., 2003; Cole et al., 2006).

In addition to an obvious need to develop aerobic qualities, it is apparent that the neuromuscular system plays an important role in optimising distance running performance (Nummela et al., 2006; Paavolainen et al., 1999c). RE is underpinned by physiological attributes, anthropometrics and biomechanics (Saunders et al., 2004a); however there is also emerging evidence demonstrating that ST enhances RE in trained distance runners (Balsalobre-Fernandez et al., 2016; Denadai et al., 2017). The proposed mechanism for this improvement relates to enhancements in neuromuscular characteristics such as lower limb stiffness and force producing ability (Albracht and Arampatzis, 2013).

There is also convincing evidence that ST is safe and effective for adolescent athletes (Behringer et al., 2011). Current guidelines suggest that adolescents should participate in 2-3 supervised RT sessions per week (Lloyd et al., 2014). Studies that have investigated the effects of RT in youth populations have tended to focus on the development of strength-related qualities in pre-pubertal and peri-pubertal participants, which underpin a variety of different sports skills. RT can also positively influence sprint performance (5-40 m), beyond that which would be expected with maturation alone (Rumpf et al., 2012). Mikkola and co-authors (2007) provide the only study to investigate the impact of a ST intervention on markers of performance in post-pubertal runners (16-18 years). Replacing 19% of total running volume with explosive ST exercises for eight weeks improved neuromuscular and anaerobic characteristics, but without any significant impact on aerobic performance markers. The ST activities (sprints, jumps and ERT) were performed in low frequency (each on average once per week), and RT primarily targeted single-joint actions. It is recommended that distance runners incorporate 2-3 ST sessions per week (Denadai et al., 2017), and utilise multi-joint closed-chain exercises, which provide a high level of mechanical specificity to the running action (Beattie et al., 2014). Therefore the effect of a ST programme, involving multi-joint resistance exercises performed more than once per week by adolescent runners, on determinants of distance running performance remains unknown.

6.1.1 Study Aim

This thesis principally aims to examine the efficacy of strength-based exercise on distance runners with an experimental focus on adolescent runners. Accordingly, the purpose of this study was to examine the effect of supplementing post-pubertal adolescent distance runners with ST on the physiological and strength-related indicators of performance. It was hypothesised that the addition of ST would result in superior improvements in RE, s$\dot{V}O_{2max}$, maximal speed and strength measures compared to the CG.

6.2 Methods

6.2.1 Study Design

To address the hypothesis of the study a randomised control trial (Registered identification: researchregistry1933) was used to investigate the effect of a ten week ST intervention on key performance indicators and body composition in a group of competitive adolescent distance runners. Following baseline testing, participants were assigned to a strength training group (STG) or a CG using a pre-test matched pairs approach. Participants were ranked according to their baseline RE, paired, and randomly allocated to either the STG or CG. This approach reduces the bias associated with randomisation, since it decreases the likelihood of differences between study groups at baseline (Atkinson and Nevill, 2001). Both groups were instructed to continue their normal running training throughout the study period. The study took place during early off-season training period, therefore participants were predominantly performing high volume, low intensity running. Participants maintained training logs (see Appendix G), which detailed their daily running volume and the pace associated with each training session. In addition to their running training, the STG performed two weekly ST sessions for the duration of the study. Following the intervention period, participants in both groups returned for follow-up testing.

6.2.2 Participants

A sample size estimation of *n*=20 was calculated based upon statistical power of 80%, at a 5% probability threshold, and an ES of 0.67 for the primary outcome variable, RE. TE and MDC_{95} for RE were derived from the reliability study in this population (Study 2, Chapter 5). Based upon an anticipated 20% drop-out, 25 participants (13 female, 12 male; mean ±SD age: 17.2 ±1.2 years, range: 15.2-18.8 years) initially volunteered to take part.

6.2.3 Procedures

Testing took place over two days before and after the intervention period. The first testing session involved measurements of anthropometrics, a submaximal running assessment and a maximal running test (see Section 3.5 for protocols). Following thirty minutes of passive recovery, participants were familiarised with the speed and strength tests. The second testing session took place 48-72 h later, and was used to test participant's maximal speed, and force-producing capabilities under dynamic and isometric conditions (see Section 3.7 for protocols). Every effort was made to schedule testing sessions on the same days pre- and post-intervention to maximise the likelihood that participants would adhere to requests to adopt a similar pattern of exercise and diet in the 48 h prior.

6.2.4 Measurements

The physiological and biomechanical variables measured as part of this study are described in Section 3.6 and 3.7 respectively. For measures influenced by body size, the allometric scaling exponents obtained in the reliability study (Study 3, Chapter 5) were applied.

6.2.5 Strength Training Prescription

The STG supplemented their programme with two sessions (60-70 min duration) of ST per week, each separated by 2-4 days. Following a week of familiarisation with exercise technique and equipment, participants completed a ten week programme of progressive ST, as shown in Table 6.1. Recent work has indicated that 6-8 week programmes elicit relatively small changes in RE, whereas programmes of ten weeks or longer provides moderate-large effects (Denadai et al., 2017). Each session commenced with a warm-up designed to enhance movement skill and mobility. The second part of the session involved plyometric- and sprinting-based exercises designed to improve explosive- and reactive-strength. The final part of each session was dedicated to RT primarily using free weights (barbells and dumbbells). Exercises were selected that possessed similar kinematic characteristics to the running action. Every session was supervised by professionally accredited S&C coaches. Intensity of each exercise was moderated based upon each participant's technical ability and perceived effort, with load on RT exercises typically progressing by 5-10% per week within a mesocycle. A selection of photographs of participants performing the ST intervention is shown in Figure 6.1.

6.2.6 Statistical Analysis

An ANCOVA was performed on each dependent variable using baseline scores as the covariate, which adjusts for any chance imbalance between the STG and CG. The assumptions associated with ANCOVA were verified for all variables via Levene's Test for homogeneity of variance, Shapiro-Wilk Test for the assumption of normality, and a customised ANCOVA model to assess homogeneity of regression. A Multivariate Analysis of Variance with a Bonferroni post-hoc correction was used to compare the data from training logs between groups. Significance was accepted at the $p<0.05$ level with a 95% CI.

Effect sizes and MBI terms were identified to provide a more qualitative interpretation of the extent to which changes observed were meaningful. Effect sizes were calculated as a ratio of the difference between the mean change value for each group and the pooled SD at baseline for all participants. The process used to obtain the MBIs is described in Section 3.8. Inter-individual responses to the intervention were calculated using the formula identified in Section 3.8. In this instance, it is more appropriate to use the SD of the CG change value as the comparator variable, rather than the TE derived from the reliability study (Chapter 5) in this population, as within-subject biological variation is likely to increase over time (Hopkins, 2000).

Table 6.1. Ten week programme followed by the strength training group (2 days$\cdot$week^{-1}). All exercises were prescribed as sets x repetitions (unless stated). Inter-set recovery duration was 90 s and 180 s for plyometrics and resistance training respectively.

Mesocycle	Weeks 1-3	Weeks 4-6	Weeks 7-10
Plyometrics	Box jump 3x6 A-skip 3x15 m Hurdle jump and land 3x6	Single leg box jump 3x6 High-knees 3x15 m Hurdle jumps 4x6	Depth jumps 3x6 Sprints 3x30 m Hurdle jumps 4x8
Resistance training	Back squat 3x8 Romanian deadlift 3x8 Single leg press 2x8 Calf raise 2x12	Back squat 3x8 Rack pull 3x8 Single leg press 3x8 Calf raise 3x12	Back squat 3x6 Deadlift 3x6 Step-ups 3x8 Calf raise 3x12

Figure 6.1. Photographs showing examples of exercises used in the strength training intervention.

6.3 Results

6.3.1 Group Characteristics

Based upon maturity offset values, all participants were considered post-pubertal (≥ 1.0 year), even when the standard error associated with the predictive equation was accounted for (Moore et al., 2015). Seven participants withdrew during the course of the study for the following reasons: injury (STG *n*=3, CG *n*=1), illness (STG *n*=1), time commitment (CG *n*=1), voluntary dropout (CG *n*=1). The injuries that occurred in the STG were diagnosed as overuse type injuries that could not be directly attributed to the intervention. No other adverse effects were reported during the intervention period. The final sample consisted of nine participants in the STG (5 females, 4 males) and nine in the CG (5 females, 4 males). Group characteristics are shown in Table 6.2, with $\dot{V}O_{2max}$ shown as a ratio to body mass for comparative purposes.

Table 6.2. Participants characteristics for each group. sLTP = speed at lactate turnpoint

	STG (*n*=9)	CG (*n*=9)
Age (years)	16.5 ±1.1	17.6 ±1.2
Body mass (kg)	57.8 ±6.1	58.5 ±9.5
Stature (cm)	170.2 ±6.8	171.6 ±6.5
Maturity offset (years)	3.1 ±1.3	3.9 ±1.1
1500 m time (s)	274.9 ±21.4	264.1 ±15.4
$\dot{V}O_{2max.}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	59.2 ±9.3	61.7 ±5.9
sLTP ($km \cdot h^{-1}$)	14.0 ±2.4	14.9 ±1.1
Running duration ($min \cdot wk^{-1}$)	180.6 ±84.9	195.6 ±86.9

6.3.2 Training History

Table 6.3 displays a summary of the training undertaken by participants during the intervention period. Participants typically undertook 2-3 extensive interval training sessions per week at sLTP or faster. These were performed on the same days across the cohort. The remaining volume of running was undertaken at speeds below sLTP, however inter-individual variation was high (135 ±74 $min \cdot week^{-1}$). No significant differences (p>0.05) between groups were noted in total training time, total running duration, running at low (<sLTP) and high (>sLTP) intensities (ES: 0.17) and aerobic cross-training (ES: 0.01). However moderate effect sizes (0.6-0.7) were observed for the difference in total running duration in favour of the CG. ST time differed significantly between groups (F=44.96, p<0.001, ES: 1.67). Engagement with ST was high in the STG, with all participants completing ≥ 85% of sessions over the ten week intervention.

Table 6.3. Mean ± standard deviation time spent (min·week^{-1}) performing various training activities during the intervention period. sLTP = speed at lactate turnpoint, STG = strength training group, CG = control group, ES = effect size. * indicates significantly different (p<0.05) from CG group.

	Running			Strength training	Aerobic cross-training	Combined total
	< sLTP	> sLTP	Total			
STG	109 ±69	42 ±7	151 ±85	112 ±7*	10 ±16	273 ±88
CG	160 ±73	53 ±18	213 ±88	33 ±35	10 ±18	257 ±106
ES	0.69	0.60	0.69	1.67	0.01	0.17
(interpretation)	(moderate)	(moderate)	(moderate)	(very large)	(trivial)	(trivial)

6.3.3 Body Composition and Running Measures

ANCOVA revealed no significant differences between groups post-training for body mass (F=0.98, p=0.338), skinfolds (F=4.15, p=0.060), $\dot{V}O_{2max}$ (F=0.48, p=0.499), s$\dot{V}O_{2max}$ (F=1.11, p=0.308), RE at LTP (F=0.57, p=0.463), RE at LTP -1 km·h^{-1} (F=1.39, p=0.256), RE at LTP -2 km·h^{-1} (F=2.34, p=0.147), s2mMol·L^{-1} (F=0.54, p=0.474), s3mMol·L^{-1} (F<0.01, p=0.980), and s4mMol·L^{-1} (F=0.01, p=0.917). Table 6.4 shows changes in body composition and physiological parameters for each group and between group comparisons. Body mass displayed a mean increase of (95% CI) 0 to 2.4% in the STG group, which was 'most likely trivial' compared to the CG (ES: 0.08). Skinfold measures also exhibited minimal changes in both groups (ES: 0.24). $\dot{V}O_{2max}$ displayed trivial changes (ES: 0.07) in both groups, and s$\dot{V}O_{2max}$ improved in the STG by only a small margin (95% CI: -2.0 to 8.9%), which compared to the CG was 'likely trivial' (ES: 0.34). RE improved between 3.2-3.7%, and by a magnitude that approximated the MDC_{95} values at all three speeds in the STG group, however increases were relatively small (ES: 0.31-0.51) and only considered 'possibly beneficial'. Figure 6.2 shows the change in average RE for three speeds, which was also considered 'possibly beneficial' (ES: 0.44) compared to the CG. sFBLC improved to a small extent (3.4-5.8%) in both groups, but between group effects were trivial (ES: 0.09-0.10). Within-group differences were considered 'likely beneficial' or 'very likely beneficial' for both groups.

Table 6.4. Changes in anthropometrics and physiological parameters in both groups. CG = control group, CI = confidence interval, LTP = lactate turnpoint, MDC_{95} = minimal detectable change for 95% confidence interval, $s\dot{V}O_{2max}$ = speed associated with maximal oxygen uptake, s = speed, STG = strength training group

	Group	Pre	Post	% change (95% CI)	Effect size (interpretation)	MDC_{95}	Magnitude based inference
Anthropometrics							
Body mass (kg)	STG	57.8 ±6.1	58.5 ±5.9	0 - 2.4	0.08 (trivial)	0.7	Most likely trivial
	CG	58.5 ±9.5	58.6 ±8.9	-1.7 - 2.1			
Skinfold (mm)	STG	36.6 ±13.2	37.9 ±14	-2.2 – 9.3	0.24 (small)	2.6	Most likely trivial
	CG	29.8 ±8.6	28.3 ±6.5	-13.4 – 3.7			
Maximal running							
$\dot{V}O_{2max}$ (L·min^{-1})	STG	3.44 ± 0.76	3.44 ± 0.71				
	CG	3.62 ± 0.52	3.66 ± 0.62				
$\dot{V}O_{2max}$ (ml·kg$^{-0.67}$·min^{-1})	STG	229.2 ±41.3	227.5 ±36.2	-4.8 – 3.3	0.07 (trivial)	7.5	Most likely trivial
	CG	241.2 ±24.2	242.0 ±21.5	-7.5 – 8.3			
$s\dot{V}O_{2max}$ (km·h^{-1})	STG	16.8 ±2.4	17.3 ±2.6	-2.0 – 8.9	0.34 (small)	0.9	Likely trivial
	CG	17.8 ±0.8	17.8 ±1.7	-6.2 – 5.3			
Running economy (kJ·kg$^{-0.67}$·km^{-1}), absolute values are shown in brackets (kJ·km^{-1})							
LTP	STG	18.7 ±1.3 (278.0 ± 23.6)	18.1 ±1.4 (271.9 ± 25.4)	-7.5 – 1.1	0.31 (small)	0.6	Possibly beneficial
	CG	18.5 ±1.3 (278.7 ± 35.9)	18.3 ±0.9 (276.4 ± 37.4)	-5.4 – 3.1			
LTP -1 km·h^{-1}	STG	18.8 ±1.2 (279.9 ± 20.5)	18.1 ±1.5 (277.3 ± 22.2)	-6.9 – 0.3	0.47 (small)	0.7	Possibly beneficial
	CG	18.6 ±1.4 (280.0 ± 39.4)	18.5 ±1.1 (281.9 ± 40.2)	-4.5 – 3.9			
LTP -2 km·h^{-1}	STG	19.2 ±1.4 (288.6 ± 23.5)	18.5 ±1.6 (272.8 ± 25.1)	-7.3 – 1.1	0.51 (small)	0.8	Possibly beneficial
	CG	18.8 ±1.3 (283.0 ± 39.2)	18.7 ±1.2 (279.9 ± 39.8)	-4.4 – 3.1			

Speed at fixed blood lactate concentrations							
s2mMol·L^{-1} (km·h^{-1})	STG	13.0 ±2.6	13.6 ±2.6	1.5 – 7.7	0.09 (trivial)	0.4	Very likely trivial
	CG	13.9 ±1.5	14.7 ±1.4	2.9 – 8.6			
s3mMol·L^{-1} (km·h^{-1})	STG	14.1 ±2.5	14.7 ±2.6	1.4 – 7.1	0.09 (trivial)	0.3	Unclear
	CG	15.1 ±1.2	15.7 ±1.4	2.0 – 6.6			
s4mMol·L^{-1} (km·h^{-1})	STG	14.9 ±2.4	15.4 ±2.5	1.3 – 6.7	0.10 (trivial)	0.3	Unclear
	CG	15.8 ±1.0	16.4 ±1.4	1.3 – 6.3			

Table 6.5. Changes in speed and strength measures in both groups. CG = control group, CI = confidence interval, MDC_{95} = minimal detectable change for 95% confidence interval, MVC = maximal voluntary contraction, STG = strength training group, $vGRF_{jump}$ = vertical ground reaction force during squat jump test. * significantly different to CG (p<0.05)

	Group	Pre	Post	% change (95% CI)	Effect size (interpretation)	MDC_{95}	Magnitude based inference
20 m sprint (s)	STG	2.79 ±0.22	2.69 ±0.19*	-5.4 to -1.8	0.32 (small)	0.03	Very likely beneficial
	CG	2.64 ±0.24	2.62 ±0.23	-1.5 - 0			
Peak displacement (m)	STG	0.26 ±0.03	0.27 ±0.04	0 – 7.7	0.10 (trivial)	0.03	Unclear
	CG	0.26 ±0.05	0.27 ±0.05	-3.8 – 11.5			
$vGRF_{jump}$ ($N \cdot kg^{-0.76}$) Absolute values in brackets (N)	STG	58.7 ±2.3 (1288 ±116)	62.3 ±6.9 (1386 ±181)	-1.9 – 14.1	0.93 (moderate)	10.1	Most likely trivial
	CG	60.7 ±5.9 (1344 ±207)	60.2 ±9.3 (1348 ±307)	-11.2 – 9.2			
Peak RFD ($N \cdot s^{-1}$)	STG	8602 ±1688*	11,150 ±3116	13.8 – 44.0	0.55 (small)	3650	Likely trivial
	CG	10,269 ±2999	11,448 ±3097	-6.3 – 37.7			
MVC ($N \cdot kg^{-0.61}$) Absolute values in brackets (N)	STG	159.3 ±28.0 (1905 ±391)	183.9 ±26.5* (2221 ±387)	6.3 – 24.5	0.86 (moderate)	23.7	Possibly beneficial
	CG	159.4 ±25.7 (1917 ±383)	161.5 ±37.1 (1965 ±540)	-9.4 – 12.5			

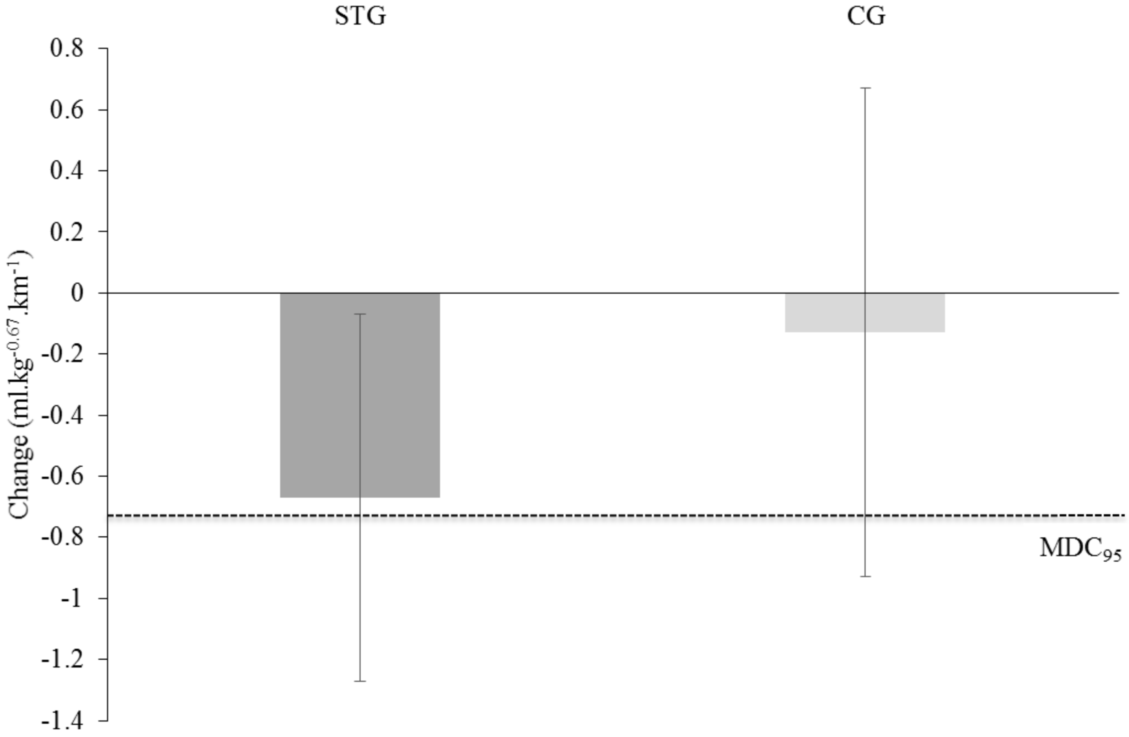


Figure 6.2. Change in average running economy in strength training group (STG) and control group (CG). Minimal detectable change at 95% confidence (MDC_{95}) is shown as the dashed line. Error bars represent the 95% confidence interval for the mean change.

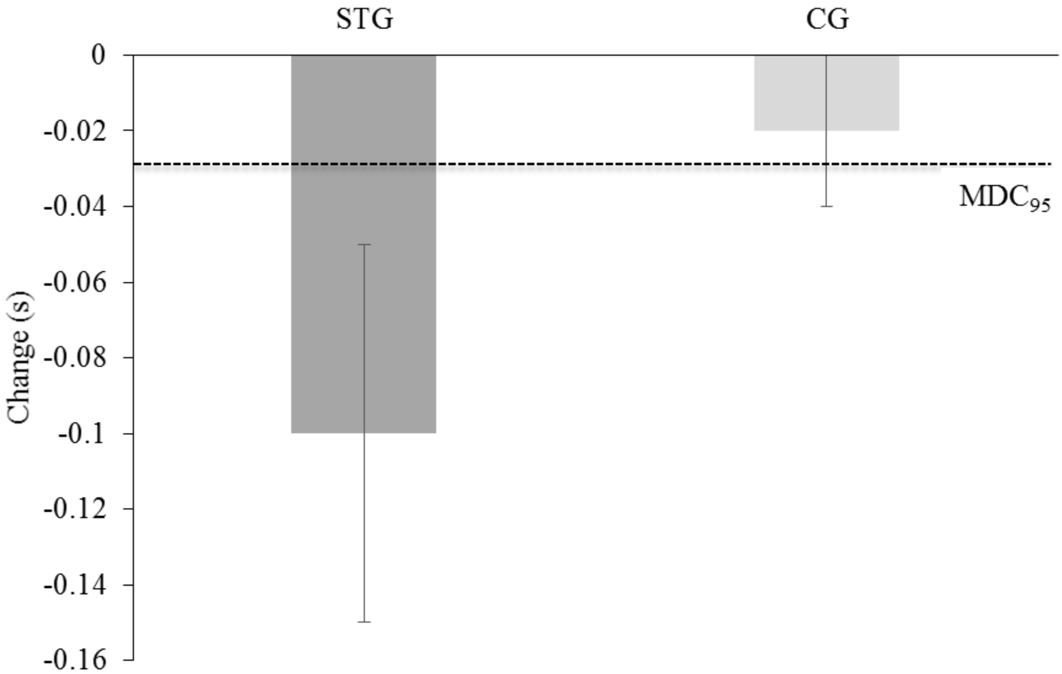


Figure 6.3. Change in 20 m sprint time in strength training group (STG) and control group (CG). Minimal detectable change at 95% confidence (MDC_{95}) is shown as the dashed line. Error bars represent the 95% confidence interval for the mean change.

6.3.4 Speed and Strength Measures

As shown in Figure 6.3, 20 m sprint time improved by -0.10 s (95% CI: 1.8-5.4%; ES: 0.32) in the STG, which generated a significantly faster time compared to the CG post-training ($F=7.86$, $p=0.013$) and was considered 'very likely beneficial'. The STG also displayed significantly greater MVC at follow-up ($F=5.07$, $p=0.040$; ES: 0.86) compared to the CG; a change which was deemed 'possibly beneficial' (95% CI: 6.3-24.5%, Table 6.5). The magnitude of between group change in peak displacement was 'most likely trivial' (ES: 0.10) and the difference non-significant ($F=0.18$, $p=0.682$). $vGRF_{jump}$ improved to a moderate extent (95% CI: -1.9 to 14.1%) in the STG compared to the CG (ES: 0.93) but this change was considered 'most likely trivial' in the context of the MDC_{95} threshold (Table 6.5). Peak RFD displayed significant differences between groups at baseline in favour of the CG ($F=5.865$, $p=0.029$). A small increase (95% CI: 13.8-44%; ES: 0.55) was observed in the STG, however this was not statistically significant compared to the CG change ($F=0.371$, $p=0.552$) and was qualitatively defined as a 'likely trivial' benefit.

Inter-individual differences in response could mainly be explained by the within-participant variability in change scores, as for all but one variable (RE at sLTP), the SD for pre-to-post differences was larger in the CG group compared to the STG group (see Table 6.4 and Table 6.5). In standardised units the individual responses for RE at sLTP was 0.18, which indicates that individual responses were trivial between groups.

6.4 Discussion

The primary aim of this study was to investigate the physiological effects of ten weeks of ST in a group of competitive post-pubertal distance runners. It was anticipated that the STG would demonstrate superior improvements in RE, $s\dot{V}O_{2max}$, sprint speed, and neuromuscular parameters compared to a CG. The main finding was that ST provides a small benefit (3.2-3.7%) to RE across a range of sub-maximal speeds, which can be considered 'possibly beneficial'. ST is also likely to provide significant benefits to maximal sprint speed and isometric strength in runners of this age.

The findings of this study are in agreement with those of a recent meta-analysis in mainly adult runners, which showed concurrent strength and endurance training can provide a small beneficial effect (3.9 ±1.2%) to RE over a 6-14 week period (Denadai et al., 2017). Our results are also similar to the only other study that has investigated the efficacy of ST in adolescent distance runners, which demonstrated small improvements (2.0-2.7%, ES: 0.26-0.40) in RE at 12 and 14 $km\cdot h^{-1}$, and trivial changes at 10 and 13 $km\cdot h^{-1}$ (Mikkola et al., 2007). The superior effects observed at all three speeds assessed (3.2-3.7%, ES: 0.31-0.51) may be due to the longer intervention period (10 vs 8 weeks), higher frequency of exposure to each type of ST activity (2 vs 1 $day\cdot week^{-1}$), and the choice of RT exercises (multi-joint vs single-joint). It is noteworthy that the intervention group in the Mikkola et al. (2007) study performed almost double the volume of training compared to the STG in the present study (273 ±88 vs 528 ±126 $min \cdot wk^{-1}$). Moreover, the CG in the present study spent 41% more time running than the STG (ES: 0.69). This suggests that for the adolescent distance runner, ST may be more effective than increasing endurance training volume at improving RE, at least in the short-term. It is also possible that the moderate disparity in low intensity running volume between the groups was advantageous to the STG group as less running may have facilitated the recovery process (Houmard, 1991; Spencer and Gastin, 2001). Despite the apparent trend towards an improvement in RE, it is important to note that the change scores did not exceed the MDC_{95} for any speed or an average of measurements (Figure 6.2), indicating that only a possible benefit exists at specific speeds when TE of measurement is taken into account. A longer intervention period may therefore be required to provide higher certainty that ST provides a practically significant benefit.

Neuromuscular factors, such as muscle activation and musculotendinous stiffness, play an important role in distance running (Lai et al., 2014; Paavolainen et al., 1999c), therefore strategies to enhance these qualities are likely to lead to an improvement in RE. A significant improvement in maximal force producing capability was observed in the STG (95% CI: 6.3-24.5%, ES: 0.86), which is in line with findings from previous studies in adult distance runners over a similar time frame (Damasceno et al., 2015; Skovgaard et al., 2014). The ST programme, which included plyometrics, sprinting and RT, was also shown to provide a small but 'very likely benefit' to maximal sprint speed (95% CI: 1.8-5.4%; ES: 0.32); an improvement which was more than three times higher than the MDC_{95} value. Maximal speed is an important anaerobic quality required for middle-distance running (Kadono et al., 2007), and is also related to long-distance running performance (Nummela et al., 2006; Paavolainen et al., 1999c). Maximal sprinting requires higher ground reaction forces compared to sub-maximal running (Nilsson and Thorstensson, 1989), therefore this finding supports the view that ST can improve neuromuscular characteristics during a highly functional assessment of explosive strength in runners. Peak displacement, $vGRF_{jump}$ and peak RFD displayed changes which fell well within MDC_{95} limits, thus the effect of ST on these parameters was at best trivial. The specificity of the exercises used in the ST programme (Table 6.1) may provide an explanation for this finding, since very little maximal concentric-dominant jumping was included. A relatively higher volume of near-maximal sprinting and loaded exercises that mimic a quarter-squat position were included, which appears to have provided a sufficiently high transfer of training effect to enhance 20 m sprint and MVC. The possibility that the bodyweight movement skill exercises included in the warm-up routine also contributed towards the improvements observed cannot be discounted. Dynamic postural control exercises reduce co-activation of muscles in the lower limb, which may have enhanced efficiency during running via improvements in stabilisation strategy (Moore et al., 2014b).

Despite the prediction that $s\dot{V}O_{2max}$ would improve to a greater extent in the STG, this was not the case (95% CI:-2.0 to 8.9%, ES: 0.34, 'likely trivial benefit'). $s\dot{V}O_{2max}$ provides a composite measure of physiological performance that appears to differentiate adolescent runners with greater accuracy than traditional determinants (Almarwaey et al., 2003). Our findings are in agreement with other works that utilised a similar intervention duration (Giovanelli et al., 2017; Mikkola et al., 2007), but differ from studies which lasted ≥ 14 weeks (Beattie et al., 2017; Millet et al., 2002), suggesting longer time frames may be required to realise a positive effect. It is also likely that large improvements in constituent qualities ($\dot{V}O_{2max}$, RE) are required to elicit a meaningful change in s$\dot{V}O_{2max}$. Although RE displayed small improvements, $\dot{V}O_{2max}$ showed little alteration, implying that a greater stimulus may be required to influence these variables.

Following an 11 week period of running training, it was expected that aerobic variables would exhibit improvements in a group of adolescent athletes. The intervention period provided a small (3.4-5.8%) but 'very likely' or 'likely benefit' to sFBLC in both groups, suggesting the running training caused metabolic adaptations (Billat et al., 2003), which were not augmented by ST (ES: 0.09-0.10). The lack of change in $\dot{V}O_{2max}$ in both groups corroborates findings from previous investigations (Beattie et al., 2017; Damasceno et al., 2015; Giovanelli et al., 2017; Millet et al., 2002; Skovgaard et al., 2014). Improvements in aerobic power are influenced by a variety of factors including initial training status, and the duration and nature of training conducted (Wenger and Bell, 1986). Both groups spent 25-28% of their running training above sLTP, an intensity which is likely to have provided a strong stimulus for improving $\dot{V}O_{2max}$ (Midgley et al., 2006b). Therefore it appears the study duration and the initial fitness level of participants provide the most likely explanation for the unaltered values observed. Despite the absence of change in several parameters, it is notable that ST caused no deleterious effects in physiological predictors of performance despite the STG spending ~40% less time running compared to the CG.

Increases in body mass are potentially disadvantageous to distance runners, therefore gains in muscle mass, which is often an inevitable consequence of RT, are unfavourable. Although the CI for the change in body mass in the STG did not overlap zero (95% CI: 0-2.4%), the differences between groups were 'most likely trivial' (ES: 0.08). Furthermore, any slight increase in body mass in the STG did not adversely affect the physiological variables that were allometrically scaled for body mass. Despite the association between RT and a hypertrophy response (Hakkinen, 1989), there is consensus that ST has little impact upon body mass in distance runners, at least in the short- to medium-term (Denadai et al., 2017). The interference phenomenon, which is often observed when endurance and ST are performed concurrently within the same programme, has been offered as one explanation (Baar, 2006). The impairment of muscle fibre hypertrophy is likely to occur under conditions of energy depletion (McBride et al., 2009), or when ST is performed alongside a high frequency and intensity of endurance exercise (Coffey et al., 2009). Given the relatively low volume of endurance training undertaken by the STG (Table 6.2), the interference effect was perhaps less likely. Therefore practitioners should be cognisant that gains in muscle mass may occur over longer periods if a low volume of running is performed.

6.4.1 Limitations

This study is subject to a number of limitations. Firstly, with the exception of sprint time, the measures taken in this study were laboratory-based, thus it is not known what impact the training intervention had on middle- or long-distance performance. Secondly, the cohort of participants were of both sexes and mixed event specialisms and abilities, therefore had a more homogenous group been targeted, firmer conclusions might have been possible. Thirdly, the scaling exponents utilised for normalisation of body mass were derived from relatively small samples ($n \leq 42$), which may have generated small errors during the calculation of values. Although it is unlikely that these errors are sufficiently large to alter the findings of this study (see Section 5.4.3), the changes observed in RE were equal to or slightly less than the MDC_{95} at each speed (Table 6.4), therefore a more accurate scaling factor may have provided greater confidence that the changes observed were meaningful. Fourth, it is noteworthy that the group difference (19.4%) between baseline values for peak RFD was statistically significant (p=0.029) and higher than the TE of measurement (11.2%) identified in Study 3 (see Table 5.5). This finding was not observed for peak displacement or other strength metrics, therefore it is unclear why this discrepancy occurred. Nevertheless, this bias in peak RFD pre-test scores did not appear to influence findings, as although the STG improved by a greater amount compared to the CG (28.9% vs 15.7%), the change was non-significant (p>0.05) and did not exceed the MDC_{95} value (33.1%), thus was deemed a 'likely trivial' effect. Finally, the study was conducted during the off-season, which was characterised by training of a more extensive nature, known to cause interference with strength adaptation (Baar, 2006). It is not known what effect a ST programme would have on physiological parameters during a different training phase, particularly one that had a larger emphasis on intensive training.

6.4.2 Conclusions

In conclusion, the addition of low frequency (2 days$\cdot$week^{-1}) ST to the programme of an adolescent distance runner is 'possibly beneficial' for RE at specific speeds, and very likely to benefit maximal sprint speed, which are both important factors for middle- and long-distance running performance. It was speculated that changes in neuromuscular characteristics, such as maximal force producing capability, underpin the small improvements in RE observed. A ten week period of ST was insufficient to alter $s\dot{V}O_{2max}$, therefore further studies are required to investigate the time course of change in this and other determinants. There appears to be little risk that ST increases body mass; any change over a period of 2-3 months is likely to be trivial.

6.5 Perspective

Two primary aims of this thesis relate to examining the acute and chronic effect of strength-based exercise on determinants of distance running performance, specifically in adolescent distance runners. Chapter 2 presented the outcomes of ST interventions in adult distance runners (Study 1; Section 2.5) and the benefits of ST for adolescent athletes (Section 2.7). Despite an abundance of literature in these areas, there is a shortage of high quality investigation specifically on the efficacy of ST for adolescents, who have ambition to excel in distance running. Interestingly, it was observed that a high proportion of competitive junior (under-20) distance runners include ST activities in their training regimen compared to their more senior counterparts (Study 2; Chapter 4). This study therefore formed the cornerstone of the experimental work in this thesis. To quantify the error in measurement associated with tests for important physiological- and strength-variables, a reliability study was first undertaken (Study 3; Chapter 5). Results of the reliability study also allow qualitative inferences to be made that have real-world relevance, based upon the uncertainty in observed values from an experiment.

Results from this Chapter suggest that ten weeks of ST added to the training routine of a post-pubertal distance runner is ‘possibly beneficial’ (ES: 0.31-0.51) for RE at several sub-maximal running speeds. A reduction in metabolic cost of running should theoretically allow runners to travel faster for the same level of effort, or expend less energy for a given submaximal speed. Either way, this is likely to augment physiological adaptation long-term by providing a greater overload or facilitating recovery due to less fatigue. Additionally, maximal sprint speed is very likely to benefit from a ST intervention. This finding has direct tangible benefits for high-intensity sprint interval sessions and middle-distance race performances in particular.

Although the chronic responses to ST in distance runners is well-researched, surprisingly few studies have examined whether acute benefits can be achieved following a short bout of strength-based exercise (see Section 2.6.4). A large body of evidence has also explored the acute effects of various LCAs on explosive power performance, thus a large gap in the literature exists surrounding acute potentiation protocols for endurance performance. Given the mechanisms that underpin a PAP effect (see Section 2.6.3), a high-performing group of young middle-distance runners represent a sub-population of endurance athletes who might be expected to generate a relatively high PAP response, if an appropriate LCA is prescribed. Consequently, Chapter 7 explores this hypothesis by investigating the acute effect of a LCA on performance-related outcomes in a group of male adolescent middle-distance runners.

CHAPTER 7

ACUTE POTENTIATING EFFECT OF DEPTH JUMPS ON RUNNING ECONOMY AND TIME TO EXHAUSTION IN MALE JUNIOR DISTANCE RUNNERS

(Study 5)

Published papers from this chapter:

Blagrove, R. C., Holding, K. M., Patterson, S. D., Howatson, G. and Hayes, P. R. (2018) Efficacy of depth jumps to elicit a post-activation performance enhancement in junior endurance runners. *Journal of Science and Medicine in Sport*. Published ahead of print. Doi: 10.1016/j.jsams.2018.07.023.

7.1 Introduction

Warm-up activities are commonplace in the pre-training and competition routine of endurance athletes. Warm-up strategies for distance runners typically aim to achieve acute metabolic and cardiovascular adjustments, which enhance the $\dot{V}O_2$ kinetic response (Jones et al., 2003a). Distance running performance is underpinned by several important physiological determinants, which are limited by metabolic and cardiovascular factors, however neuromuscular characteristics also play an important role (Thompson, 2017). It is currently unknown whether high-intensity strength-based activities incorporated into a warm-up are capable of potentiating the neuromuscular system, thus providing additional benefits to the determinants of performance in distance runners.

For short-duration athletic tasks, such as sprints and jumps, there is a large body of evidence demonstrating possible improvements in performance 5-12 min after completion of a ballistic exercise (e.g. plyometrics) or a heavy resistance exercise (>85% 1RM) (Maloney et al., 2014; Seitz and Haff, 2016). The PAP phenomenon is believed to be responsible for this effect, which is underpinned by several physiological mechanisms including phosphorylation of MLC, an increase in motor unit recruitment and changes in limb stiffness (Maloney et al., 2014; Tillin and Bishop, 2009). Although, these mechanisms have been shown to facilitate a short-term improvement in explosive power performance there has been speculation that endurance-related outcomes may also benefit (Hamada et al., 2000).

Type II muscle fibres possess a greater capacity for phosphorylation of MLC (Vandervoort et al., 1983), therefore middle-distance runners who possess a relatively high proportion of type II muscle fibres compared to longer-distance specialists (Costill et al., 1976a), are most likely to benefit from a PAP protocol (Hamada et al., 2003). Older adults and athletes who have spent extended periods of time participating in endurance training are more also likely to possess a low percentage of type II muscle fibres (Abernethy et al., 1990; Nilwik et al., 2013). A group of high-performing younger distance runners therefore seem to represent a population of endurance athletes who might benefit from a PAP protocol.

Improvements in RE (Balsalobre-Fernandez et al., 2016; Denadai et al., 2017) and TT performance (Beattie et al., 2014) have been reported following a chronic ST intervention, however only a few studies have reported how these methods might acutely enhance these parameters (Barnes et al., 2015; Feros et al., 2012; Silva et al., 2014). A series of sprints (6x10 s) wearing a weighted vest prior to an incremental treadmill run has been shown to improve peak running speed and RE compared to a warm-up which included non-weighted sprints (Barnes et al., 2015). The authors attributed changes in leg stiffness, assessed using a repeated jump-test, to the performance improvements. High-load resistance exercise has also been shown to enhance 20 km TT performance in well-trained cyclists (Silva et al., 2014). A similar finding was observed in a group of elite rowers during a 1 km TT, with power in the first 500 m displaying improvement following a series of 5x5 s isometric contractions on the rowing ergometer (Feros et al., 2012).

7.1.1 Study Aim

Simple strategies incorporated into warm-up routines, which have the potential to improve performance, are likely to be of considerable interest to athletes and their coaches. High-intensity PT has been shown to enhance RE and performance (Beattie et al., 2014) and plyometrics have been used to successfully potentiate sprint performance in athletically trained males (Bomfim Lima et al., 2011). Importantly, plyometrics do not require specialist or cumbersome equipment and can be easily utilised in a field-based setting with athletes. Based on the aforementioned information, it was hypothesised that a simple plyometric exercise would improve RE and performance. Consequently, the aim of this study was to examine the influence of performing DJ on RE and TTE in a group of elite junior middle-distance runners.

7.2 Methods

7.2.1 Study Design

The study required participants to attend the laboratory on three occasions during the off-season, each separated by 2-7 days. The first testing session involved a discontinuous submaximal incremental running assessment followed by a $\dot{V}O_{2max}$ test. After a 20 min active recovery consisting of 5-10 min jogging and slow walking, CMJ height was also assessed. On the second and third visits to the laboratory, participants completed two performance trials in a crossover design, one which included a warm-up involving a set of DJ and the other a control condition, involving unloaded quarter squats.

7.2.2 Participants

A power analysis for a crossover study design was performed using within-subject SD and MDC_{95} from the reliability study (see Chapter 5). It was identified that ten participants were required to detect a treatment difference at a two-sided 0.05 significance level with a probability of 80%.

Seventeen junior (aged 15-18 years) male middle-distance runners of national and international standard took part in this study. All participants were classified as post-pubertal (≥ 1 year) based upon a calculation of predicted maturity offset (Moore et al., 2015). The characteristics of the participants are shown in Table 7.1.

Table 7.1. Characteristics of study participants (*n*=17). SD = standard deviation, $\dot{V}O_{2max.}$ = maximal oxygen uptake, sLTP = speed at lactate turnpoint, s$\dot{V}O_{2max.}$ = speed associated with maximal oxygen uptake, CMJ = counter-movement jump.

Characteristic	Mean ± SD
Age (years)	17.6 ± 1.2
Body mass (kg)	63.4 ± 6.3
Stature (m)	1.76 ± 0.06
$\dot{V}O_{2max.}$ (mL·kg^{-1}·min^{-1})	70.7 ± 5.2
sLTP (km·h^{-1})	16.7 ± 1.4
s$\dot{V}O_{2max.}$ (km·h^{-1})	21.7 ± 1.4
CMJ (m)	0.416 ± 0.065

7.2.3 Procedures

The protocols used for the sub-maximal and maximal running tests are described in Section 3.5. The three CMJ attempts were performed, and displacement measured, as per the squat jump protocol (see Section 3.7.2), however participants did not pause in a half-squat position, and were simply instructed to jump as high as possible. Maximum CMJ height was used to individualise box height (to the nearest 0.01 m) for the DJ utilising rubber-topped stepping boxes (Perform Better, Warwickshire, UK) and squares of dense rubber matting (0.01 m thick). Participants were then familiarised with the exercises to be used in the two warm-up scenarios (DJ and control). For the DJ, participants were instructed to step off a box and rebound as high as possible whilst minimising their ground contact time. Figure 7.1 shows the laboratory environment and a participant about to commence a depth-jump repetition. The control trial involved descending into a shallow squat position (~140° knee flexion) before slowly returning to standing. This exercise was included to mask the active effect that was anticipated from the DJ and minimise the likelihood of a placebo response.

Participants completed the trials in a quasi-randomised counter-balanced order (ABBA method) to eliminate the possibility of bias caused by sequencing of trials. A visual timeline of the protocol used in the trials is shown in Figure 7.2. The two trials commenced with a warm-up at 60% $\dot{V}O_{2max}$ followed by 5 min of running at 20%Δ below $\dot{V}O_2$ at LTP. The delta value was obtained by deducting $\dot{V}O_2$ at sLTP from $\dot{V}O_{2max}$. This intensity was selected as the fastest speed that participants were still able to maintain a steady state of $\dot{V}O_2$. Following a 5 min passive recovery, participants completed six repetitions of either DJ or the control exercise. Both protocols were followed by a further 10 min of passive rest to allow neuromuscular fatigue to dissipate but maximise the likelihood of a potentiation response being realised. Immediately prior to remounting the treadmill, participants were asked to provide a rating (1-10) of perceived readiness (Ingham et al., 2013). To evaluate the effect of the intervention on RE, participants then ran for a further 5 min at 20%Δ below $\dot{V}O_2$ at LTP. This was followed by a 1 min rest and a run to exhaustion at s$\dot{V}O_{2max}$. Rest periods were used to adjust the speed of the treadmill whilst the participant stood astride the belt. Time started when the participant's feet were in contact with the belt and their hands released from the hand rails. Participants were blinded to the duration they had been running for throughout the trial.

Figure 7.1. Photograph showing the laboratory environment and set-up for DJ protocol.

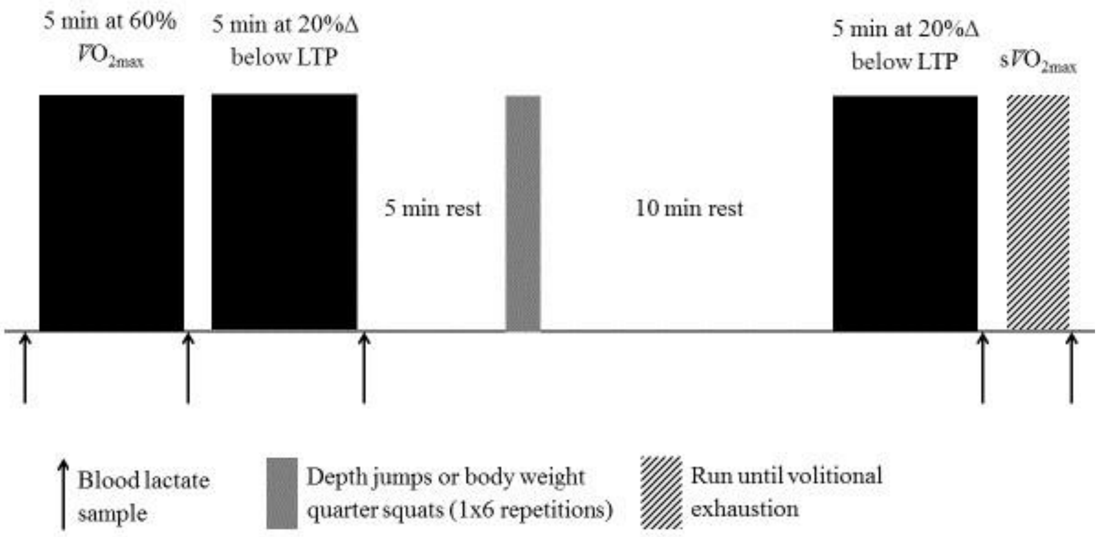


Figure 7.2. Schematic representation of each trial. $\dot{V}O_{2max}$ = maximal oxygen uptake, LTP = lactate turn-point, s$\dot{V}O_{2max}$ = speed at $\dot{V}O_{2max}$.

7.2.4 Measurements

Anthropometric measurements were recorded as described in Section 3.6.1. At the start of each testing session, participant's body mass was taken. Stature and sitting height were also measured in the first trial, for prediction of maturity offset.

RE, BL, HR, RPE and maximal measures were taken in accordance with the protocols previously described in Chapter 3 (see Sections 3.6.2 – 3.6.5). In the main trials, $\dot{V}O_2$, $\dot{V}CO_2$ and HR were averaged for the final 2 min of both 5 min stages. Time to volitional exhaustion was recorded to the nearest second for the continuous run at s$\dot{V}O_{2max}$, and BL was taken immediately after.

7.2.5 Allometric Scaling

As this study generated a larger sample size of male only participants (*n*=35), compared to the reliability study (*n*=20), an allometric scaling exponent was therefore obtained by combining baseline data from participants in the present study with male participants from the reliability study (17.3 ± 1.4 years, 62.8 ± 6.5 kg, 1.77 ± 0.06 m, 70.4 ± 7.0 $mL\cdot kg^{-1}\cdot min^{-1}$). Natural logarithms (*In*) of absolute $\dot{V}O_2$ and body mass were taken for sLTP -1 $km\cdot h^{-1}$ and linear regression was used to obtain values for the model $ln_y = ln_a + b.ln_x$, where [a] is the scaling constant and [b] is the scaling exponent correspondent to body mass. The allometric model was identified as $= 104.6\,x^{0.85}$, therefore a scaling exponent of 0.85 (95% CI = 0.53-1.17) was used in subsequent analysis of RE.

7.2.6 Statistical Analysis

For the sample of participants used to obtain an appropriate scaling value and data sets from each trial, normality of distribution was confirmed visually using Q-Q plots and objectively with a Shapiro-Wilks statistic. Prior to scaling, the assumption of homoscedasticity was assessed using a scatterplot of the standardised residual and standardised predicted variables. Equality of variances between trials was assessed with Levene's statistic. Homogeneity of regression was evaluated with a custom model ANCOVA using the trial*pre-test interaction term. Differences in pre-test values for RE, BL, HR and RPE were checked using an ANOVA.

ANCOVA models allow differences between trials to be evaluated whilst correcting for variability in pre-test values (co-variate). It was identified that a significant difference existed between trials for baseline RE in favour of the control trial (F=8.872, p=0.005), therefore change scores were used in the ANCOVA model to avoid the potential of retaining a false null hypothesis (type II error). ANOVA tests were used to identify any differences that existed between trials for perceived readiness, TTE and end BL concentrations.

Effect sizes for the measures taken during submaximal running were calculated as the difference between change scores divided by the SD of pre-test scores across both trials. For measures taken during the run to exhaustion, effect sizes are presented as a ratio between the mean difference between trials and the between-subject SD. MBI terms were calculated using MDC_{95} values from the reliability study (Table 5.4). The intensity of the 5 min runs at 20%Δ below $\dot{V}O_2$ at LTP was similar to RE at sLTP -1 $km{\cdot}h^{-1}$, and BL approximated 3 $mMol{\cdot}L^{-1}$, therefore corresponding MDC_{95} values were used in analysis.

As potentiation response appears to be related to strength status (Seitz and Haff, 2016), a partial correlation that controlled for the influence of pre-test score was performed in SPSS Statistics on the percentage change score for RE in the DJ trial and CMJ performance. Inter-individual responses were explored by calculating the true individual difference (see Section 3.8).

7.3 Results

The difference in intensity between the 5 min warm-ups that preceded both trials was negligible ($\%\dot{V}O_{2max}$: 61.2 ± 4.4% vs 60.0 ± 4.2%, ES=0.17). Table 7.2 displays the results for measures taken during submaximal running before and after the DJ and control interventions. Participants perceived readiness to perform was significantly higher (F=4.53, p=0.041, ES: 0.62) following DJ compared to the control condition. Performing DJ provided a 'possible benefit' (-3.7%, ES: 0.67) to RE, which was statistically significant compared to the control trial change (F=11.39, p=0.002). The effects on BL, HR and RPE were trivial (ES: <0.2) and non-significant (p>0.05). The effect of DJ on TTE at $s\dot{V}O_{2max}$ and BL response did not reach statistical significance, and in qualitative terms was considered 'very likely trivial' (ES: <0.2) compared to the control trial (Table 7.2).

A moderate negative correlation (r=-0.55, p=0.028) was observed between the change in RE following DJ and CMJ height after controlling for pre-intervention RE. The true individual difference for change in RE in the DJ trial was calculated as 0.19 $kJ{\cdot}kg^{-0.85}{\cdot}km^{-1}$ (95% CI: 0.15-0.23 $kJ{\cdot}kg^{-0.85}{\cdot}km^{-1}$). In standardised units (true individual difference divided by pooled pre-intervention SD), the individual responses were 0.42 (95% CI: 0.33-0.51) representing a small individual effect to the DJ intervention for RE. These individual changes in RE for the DJ trial are shown with the mean group change in Figure 7.3. Individual responses in TTE were trivial (6.5 s, ES: 0.04).

Table 7.2. Results and qualitative inferences of measures taken during submaximal running at 20%Δ below $\dot{V}O_2$ at lactate turnpoint and for the run to exhaustion at speed associated with $\dot{V}O_{2max}$. CI = confidence interval, DJ = depth jumps, C = control trial (body weight quarter squats), RPE = rating of perceived exertion (6-20 scale). * statistically significant difference compared to C (*p*<0.05)

Variable	**Trial**	**Pre-intervention**	**Post-intervention**	**Mean percentage change ± 95% CI**	**Effect size (interpretation)**	**Magnitude based inference**
Perceived readiness (1-10)	DJ	-	6.9 ± 0.9*	13.3 ± 9.8	0.62 (moderate)	-
	C	-	6.1 ± 1.3			
Submaximal running						
Running economy ($kJ \cdot kg^{-0.85} \cdot km^{-1}$)	DJ	9.35 ± 0.44 (314.0 ± 23.3)	9.00 ± 0.42 (304.9 ± 22.7)	-3.7 ± 1.3*	0.67 (moderate)	Possibly beneficial
Absolute values shown in brackets (kJ.km)	C	8.92 ± 0.41 (303.1 ± 24.9)	8.88 ± 0.41 (301.6 ± 24.9)	-0.5 ± 0.8		
Blood lactate ($mMol \cdot L^{-1}$)	DJ	2.8 ± 0.9	2.4 ± 0.8	-14.3 ± 6.1	0.15 (trivial)	Very likely trivial
	C	2.6 ± 0.8	2.3 ± 0.8	-11.5 ± 6.2		
Heart rate ($b \cdot min^{-1}$)	DJ	172 ± 10	173 ± 10	0.6 ± 0.4	0.08 (trivial)	Most likely trivial
	C	171 ± 11	173 ± 10	1.1 ± 0.6		
RPE (6-20)	DJ	12 ± 1	13 ± 1	6.8 ± 6.2	0.12 (trivial)	Very likely trivial
	C	12 ± 2	13 ± 1	5.4 ± 3.6		
Run to exhaustion						
Time to exhaustion (s)	DJ	-	160 ± 39	1.3 ± 6.5	0.06 (trivial)	Very likely trivial
	C	-	158 ± 34			
End lactate ($mMol \cdot L^{-1}$)	DJ	-	8.1 ± 2.1	2.5 ± 7.7	0.13 (trivial)	Most likely trivial
	C	-	7.9 ± 1.9			

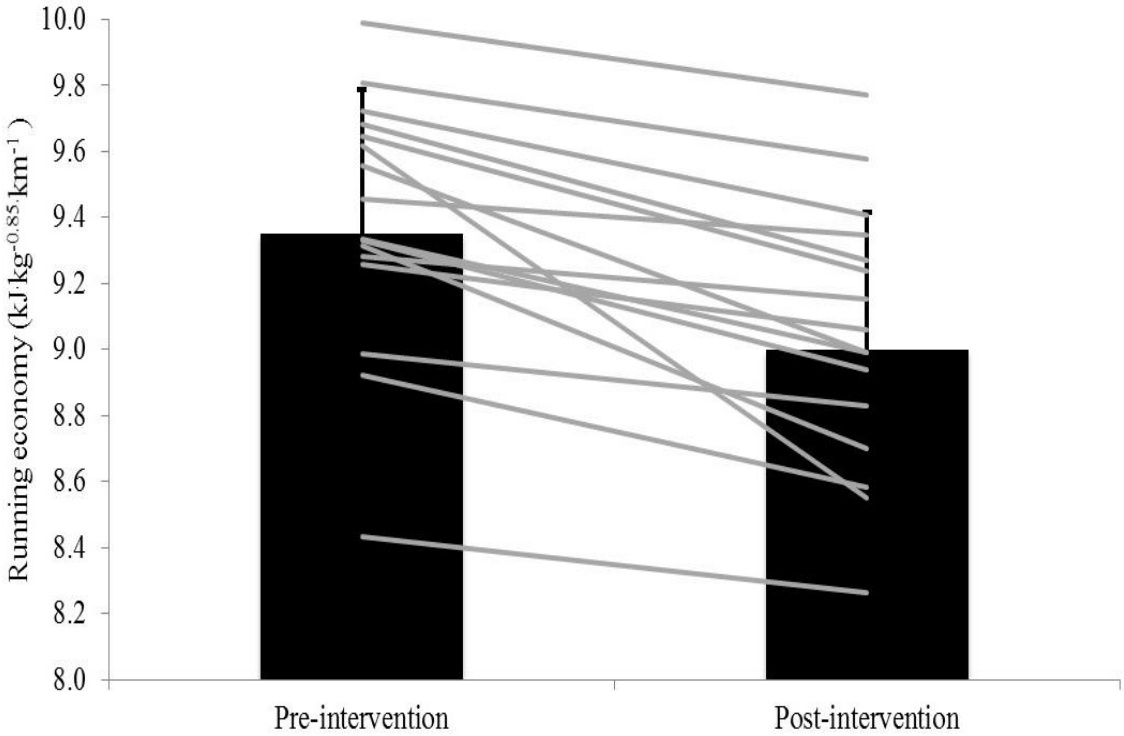


Figure 7.3. Mean change and individual values (n=17) for running economy at 20%Δ below $\dot{V}O_2$ associated with lactate turnpoint in the depth jumps trial.

7.4 Discussion

The aim of this experiment was to examine whether the inclusion of DJ in the warm-up routine of a group of high-performing junior middle-distance runners could acutely influence RE, and TTE at s$\dot{V}O_{2max}$. Findings suggest that DJ provide a significant moderate benefit (-3.7%, ES: 0.67) to RE but TTE was unaffected. This may, in part, be mediated by a higher subjective readiness to perform. In the context of MDC_{95} values, DJ were considered a 'possibly beneficial' stimulus to enhance RE. There were small differences in individual RE responses to DJ, and this appears partly attributable to an individual's explosive strength capabilities.

Despite a large body of evidence demonstrating positive acute effects from high-load resistance (Seitz and Haff, 2016) and ballistic (Maloney et al., 2014) exercise on explosive power tasks, very few studies have been conducted examining whether endurance-related parameters could also benefit. This is the first study to show significant improvements (-3.7%, ES: 0.67) in RE following a single set (6 repetitions) of high-intensity plyometric exercise compare to the change observed in a CG (p=0.002). This effect is similar in magnitude to improvements observed in RE following chronic periods (6-14 weeks) of ST in distance runners (Denadai et al., 2017). Using a similar protocol to the current study, Barnes and colleagues (2015) observed large (-6.0%, ES: 1.40) improvements in RE following 6x10 s sprints with a weighted vest (20% body mass). Similarly, Feros and co-workers (2012) found that using isometric contractions (5x5 s) on a rowing ergometer increased mean power for the first half of a 1 km rowing time trial by 6.6% (ES: 0.64). Collectively, these data suggest a moderate-large benefit for task-specific potentiation stimuli to enhance performance-related outcomes.

There were trivial differences in BL and HR during sub-maximal running between trials (ES: <0.2). This suggests that metabolic- or cardiovascular-related mechanisms are unlikely to be responsible for the change observed in RE. Acute alterations in neuromuscular characteristics, which are also known to underpin RE (Nummela et al., 2006), are therefore a more likely mechanism of effect. Indeed, acute increases in musculotendinous stiffness have previously been shown in response to a potentiation stimulus (Barnes et al., 2015; Comyns et al., 2007). A high-intensity plyometric exercise may also activate a large pool of motor units, which are then accessible during subsequent exercise (Hamada et al., 2000). Thus, for any given sub-maximal exercise performed shortly after, a lower relative intensity of activation is required, thereby reducing energy cost (Fletcher and MacIntosh, 2017). The significant difference observed between trials in perceived readiness to perform (p=0.041, ES: 0.62) is similar to findings by Ingham and colleagues (2013) and indicates that a central mechanism of effect may also have played a role in improving RE. It may also be possible that this difference in perceived readiness was simply reflective of a placebo response to the DJ, and is not an indication of a mechanism underlying the positive change in RE.

Although it is clear that endurance-trained athletes are capable of eliciting a PAP response (Hamada et al., 2000), the phenomenon is more likely to occur in stronger individuals (Seitz and Haff, 2016). This is partly confirmed by findings in the present study as explosive strength capability, measured via a CMJ, was correlated (r=-0.55, p=0.028) with change in RE following DJ. This suggests that distance runners with greater levels of explosive strength are more likely to benefit from a PAP protocol. In this study, DJ were performed from a height equal to a participants CMJ, therefore more explosive individuals received a higher stimulus than those who were less explosive. The possibility that differences in the absolute intensity of the stimulus applied explain the improvement observed in change in RE following DJ cannot be discounted.

Identification of individual responses is only possible if the random within-subject variation is accounted for by calculating the extent to which the net mean effect of an intervention differs between participants. The true individual responses to DJ were small, even when uncertainty was accounted for (ES: 0.42, 95% CI: 0.33-0.51, Figure 4.2). The overall effect of DJ, after removing the effects of random variation can therefore be summarised as -0.35 ± 0.19 $kJ \cdot kg^{-0.85} \cdot km^{-1}$ (mean ± SD of individual response) or, in standardised units (ES) 0.67 ± 0.42. Thus, the positive effect typically ranged from small (ES: 0.25) to borderline moderate-large (ES: 1.09).

TTE at $s\dot{V}O_{2max}$ and end BL were very similar between trials (ES: <0.2, p>0.05). Following a PAP-inducing stimulus, potentiation and fatigue coexist (Tillin and Bishop, 2009), therefore selecting a recovery time that allows fatigue to dissipate, yet a state of potentiation to remain, is essential to ensure a benefit is realised. In the present study, RE was measured 10 min after completion of DJ. The run to exhaustion then started 16 min after the DJ, thus any potentiation may have dissipated by this point in the trial. A similar response pattern was observed in a 20 km cycle TT after heavy (5RM) leg pressing exercise and a 10 min recovery (Silva et al., 2014). Only the first split (0-2 km) in the TT was augmented, with little difference observed in the remainder of the trial compared to a control condition (Silva et al., 2014). It is also possible that the task itself was unsuitable for any state of potentiation to be realised. As RE was significantly improved, a TTE run or TT at an intensity below maximal lactate steady state may have produced more noticeable improvements.

7.4.1 Limitations

It is important to note that the pre-intervention values for RE between trials displayed a significant difference (p=0.005) of 4.8%, which is greater than the within-subject variation recorded in the reliability study (see Chapter 5, Table 5.4). Given the design of the study, blinding of participants to the intervention they were about to perform, careful calibration of equipment, and high similarity between inter-trial warm-up intensities, it is not obvious why this difference occurred. A difference of 2.9% was present in the pre-intervention $\dot{V}O_2$ values, which is similar to intra-individual variability recorded in the reliability study (2.8%). When combined with subtle differences in body mass (0.3%) and RER values (0.7%), both in favour of the DJ trial, this appears to have generated inflated pre-intervention values in the DJ trial.

The only variable measured in this study which was not replicated in the reliability study was TTE at $s\dot{V}O_{2max}$. To generate the MBI term, the TE of the TTE from the $\dot{V}O_{2max}$ test in the reliability study was used, however this was obtained using an incremental gradient change, not at a continuous speed. Given that a trivial mean difference was noted between conditions for TTE in this study (2 ± 20 s, 1.3 ± 6.5%, ES: 0.06), it is unlikely this inaccuracy will have affected the MBI, however it cannot be discounted. Due to the nature of the two different protocols, TTE was markedly different between this investigation (159 ± 36 s) and the reliability study (376 ± 70 s), therefore the MDC_{95} percentage (10.1%) was applied to the mean result of this study and used as the threshold of effect (16 s). One alternative would have been to utilise the SWC statistic (0.2 x between-participant SD), which has been advocated for this procedure (Batterham and Hopkins, 2006). However, the SWC does not account for the TE of measurement, which may be larger. The SWC statistic for TTE would be 7 s, which evidently is far less sensitive than using the MDC_{95} percentage from TTE in the reliability study. A study by Billat and colleagues (1994) which assessed the reproducibility of TTE at $s\dot{V}O_{2max}$ in a group of male long-distance runners ($\dot{V}O_{2max}$: 69.5 ± 4.2 $mL.kg^{-1}.min^{-1}$, $s\dot{V}O_{2max}$: 21.25 ± 1.1

km.h^{-1}) similar to those used in this study, provides further perspective. Test-retest data showed a TE of 5.7% (ES: 0.42), which would generate a MDC_{95} value of 64 s (15.8%) (Billat et al., 1994). This indicates that TTE at s$\dot{V}O_{2max}$ may possess lower day-to-day stability compared to TTE in a $\dot{V}O_{2max}$ test, thus the finding that DJ provided a 'very likely trivial' effect on TTE is plausible.

The results of the reliability study indicated that measures of explosive strength possess only moderate reliability in this population (see Table 5.5). It is therefore possible that the trend for an improvement in jump height under test-retest conditions would also have been observed in this study for CMJ. If this was the case, participants in the present study would have performed their DJ from a box ~5% (1-3 cm) higher. It is not known whether this additional height would have provided a greater level of potentiation, however given the numerous other confounding variables that may also be influencing results by small margins, it seems unlikely.

7.4.2 Conclusions

Including six DJ, 10 min prior to a run just below LTP provides a moderate benefit to RE in high-performing junior male middle-distance runners. Runners who display higher levels of explosive strength seem more likely to experience a positive response. It appears less likely that continuous efforts at s$\dot{V}O_{2max}$ are likely to benefit, however this may have been influenced by the timing of the protocol in this study.

7.5 Perspective

This thesis aims to further our understanding of concurrent training for distance runners by investigating current ST practices, and examining the acute and chronic efficacy of ST exercise on physiological determinants of performance, with a specific experimental focus on adolescent runners. The study presented in this Chapter contributed to this aim by exploring the acute effect of a set of plyometric-based exercise on a range of physiological parameters associated with performance in a group of national and international adolescent middle-distance runners. Chapter 2 discussed the theoretical and evidence-based rationale for this warm-up approach in endurance-athletes and results from Study 2 (Chapter 4) indicated that a relatively high proportion (35%) of runners include PT exercises in their warm-up. RE data from Study 3 (Chapter 5) was used with values obtaining for participants in this study to generate an accurate allometric scaling exponent. This removes the confounding influence of body mass from an expression of RE.

Findings from the present study suggest that middle-distance runners should experiment with incorporating a set of DJ into their warm-up routine 10 min prior to a continuous run at a speed just under LTP. Theoretically, an improvement in RE should allow a higher absolute speed to be attained for the same relative submaximal intensity, thus augmenting the training response. It is likely that runners with higher levels of explosive strength will experience a greater improvement in RE. Therefore it may be possible that by increasing strength qualities long-term using RT may enable runners to achieve a greater level of potentiation that provides an advantage to performance.

CHAPTER 8

GENERAL DISCUSSION

Published papers from this chapter:

Blagrove, R. C., Howe, L. P., Howatson, G. and Hayes, P. R. (2018) Strength and conditioning for adolescent endurance runners. *Strength and Conditioning Journal*. Doi: 10.1519/SSC.0000000000000425

8.1 Summary of Findings

Middle- and long-distance running performance is constrained by several important aerobic and anaerobic parameters. In particular, RE displays large inter-individual variability and is influenced by a number of biomechanical and neuromuscular factors that can be enhanced with non-running based training methods. The efficacy of ST for distance runners has received considerable attention in the literature, however to-date the results of these studies had not been fully synthesised in a review on the topic.

The first study in this thesis was a systematic review, which aimed to provide a comprehensive critical commentary on the current literature that has examined the effects of ST modalities on the physiological determinants of middle- and long-distance runners. Electronic databases were searched using a variety of key words relating to ST exercise and distance running. This search was supplemented with citation tracking. To be eligible for inclusion, a study was required to meet the following criteria: participants were middle- or long-distance runners with ≥ 6 months experience, a ST intervention (HRT, ERT and/or PT) lasting ≥ 4 weeks was applied, a running only CG was used, data on one or more physiological variables was reported. Two independent assessors deemed that 24 studies fully met the criteria for inclusion. PEDro scores, which assessed the methodological rigor of each study revealed internal validity of 4, 5 or 6 for the works reviewed. RE was measured in 20 of the studies and generally showed improvements (2-8%) compared to a CG, although this was not always the case. TT performance (1.5 km – 10 km) and anaerobic speed qualities also tended to improve following ST. Other parameters such as $\dot{V}O_{2max}$, s$\dot{V}O_{2max}$, BL and body composition were typically unaffected by ST. It was concluded that the addition of 2-3 ST sessions per week, which include a variety of ST modalities are likely to provide benefits to RE, TT performance and sprint performance in middle- and long-distance runners. Importantly for the distance runner, body mass does not appear to increase following a ST intervention lasting ≤14 weeks.

Despite the consensus surrounding the advantages of concurrent strength- and endurance-training for a distance runner, S&C practices of distance runners are largely unknown. The second study in this thesis therefore aimed to explore the S&C habits of competitive middle- and long-distance runners and also examined whether reported frequency of injuries were influenced by training behaviours. An online survey was completed by 1883 distance runners (≥ 15 years old). All runners who raced competitively were included in data analysis (*n*=667). Distance runners mainly engaged with S&C activities to lower risk of injury (63.1%), and improve performance (53.8%). The most common activities utilised were stretching (86.2%) and core stability exercises (70.2%). RT and PT were used by 62.5% and 35.1% of runners respectively. Junior (under-20) runners include PT, running drills and circuit training more so than masters runners. Significantly more international standard runners engaged in RT, PT and fundamental movement skills training compared to competitive club runners. Middle-distance (800 m-3000 m) specialists were more likely to include RT, PT, running drills, circuit training and barefoot exercises in their programme than longer-distance runners. Injury frequency was associated with typical weekly running volume and run frequency. S&C did not appear to confer a protection against the number of injuries runners experienced.

Recommendations provided by several authorities and international organisations indicate that ST offers a range of health and performance benefits to youth athletes (Behm et al., 2008; Bergeron et al., 2015; Lloyd et al., 2016; Lloyd et al., 2014). Results from the survey (Study 2) revealed a relatively high proportion of junior (under-17 and under-20) runners choose to include ST activities in their training routine. The systematic review (Study 1) also identified a lack of literature specifically on the post-pubertal adolescent age-group, which is typically the period that young athletes will elect to specialise in a sport of their choosing (Lloyd et al., 2016; Lloyd and Oliver, 2012; Myer et al., 2016). A ST intervention with post-pubertal adolescent distance runners therefore formed the cornerstone of this thesis (Study 4) to address this absence of literature.

To enable effective interpretation of data in the experimental studies of this thesis two investigations were carried out in young distance runners (Study 3), one which aimed to quantify the intra-individual reliability of a number of physiological variables and the other a reliability study into biomechanical variables. For the physiological variables, sixteen (8 male, 8 female) participants (16.7±1.4 years) performed a sub-maximal incremental running assessment followed by a maximal running test, on two occasions separated by no more than seven days. A number of physiological parameters were assessed including: $\dot{V}O_{2max}$, s$\dot{V}O_{2max}$, RE, RPE, and speed and HR at FBLC. $\dot{V}O_{2max}$ and RE were scaled for differences in body mass using a power exponent derived from a larger cohort of young runners (*n*=42). RE was expressed as oxygen cost and energy cost at the sLTP and the two speeds prior to sLTP. Results of ANOVA revealed an absence of systematic bias between trials except for BL taken immediately after the $\dot{V}O_{2max}$ test, and RPE at sLTP -2 km.h^{-1}. Reliability indices for $\dot{V}O_{2max}$, s$\dot{V}O_{2max}$, RE, and speed and HR at FBLC showed a high level of reproducibility across all parameters (TE: ≤ 2%, ICC: > 0.8, ES: < 0.6). Expressing RE as energy cost provided superior reliability than using oxygen cost (TE ~1.5% vs ~2%).

To assess the reproducibility of maximal speed and strength-related variables, twelve (6 male, 6 female) participants (17.8±1.4 years) were familiarised with a 20 m sprint test, a squat jump assessment and an isometric quarter squat protocol before performing two identical trials separated by 2-5 days. Maximal speed and squat jump displacement exhibited excellent day-to-day consistency (TE: <4.9%, ICC: >0.9, ES: <0.3). Conversely, $vGRF_{jump}$, peak RFD during the squat jump and MVC during the isometric quarter squat possessed moderate levels of reliability (TE: 5-11%, ICC: 0.49-0.65, ES: 0.62-0.79).

Study 4 in this thesis was a randomised control trial, which aimed to examine the effect of ST on several important physiological and neuromuscular qualities associated with distance running performance in post-pubertal adolescent distance runners. Participants (*n*=25, 13 female, 17.2 ±1.2 years) were paired according to their sex and RE and randomly assigned to a ten week STG, or a CG who continued their regular training. The STG performed twice weekly sessions of plyometric, sprint and resistance training in addition to their normal running. Outcome measures included those assessed as part of the reliability study. Eighteen participants (STG, *n*=9, 16.1 ±1.1 years; CG, *n*=9, 17.6 ±1.2 years) completed the study. The STG displayed small improvements (3.2-3.7%, ES: 0.31-0.51) in RE that were inferred as 'possibly beneficial' across three submaximal speeds. Trivial or small changes were observed for body composition variables, $\dot{V}O_{2max}$ and s$\dot{V}O_{2max}$, however the training period provided likely benefits to sFBLC in both groups. ST elicited a 'very likely benefit' and a 'possible benefit' to sprint time (ES: 0.32) and MVC (ES: 0.86) respectively.

In contrast to the high number of studies that have investigated the chronic effects of ST on parameters relating to distance running performance, there is currently a dearth of literature that has explored whether a potentiation response can be achieved following a short bout of strength-based exercise. Study 5 of this thesis examined the effect of performing a set of pre-exercise DJ on RE and TTE at s$\dot{V}O_{2max}$ in a group of high-performing adolescent middle-distance runners. Following baseline testing, seventeen national- and international-standard male distance runners (17.6 ± 1.2 years, 70.7 ± 5.2 $mL \cdot kg^{-1} \cdot min^{-1}$) completed two trials organised in a randomised crossover design. After a 5 min warm-up at 60% $\dot{V}O_{2max}$, participants performed a 5 min run at 20%Δ below the $\dot{V}O_2$ corresponding with LTP to determine pre-intervention RE. Participants then completed either six DJ from a box height equivalent to their best CMJ or a control condition involving body weight quarter squats. After a 10 min passive recovery, another 5 min sub-maximal run was performed followed by a run to exhaustion at s$\dot{V}O_{2max}$. Compared to the control trial, DJ produced moderate significant improvements (-3.7%, ES: 0.67, p=0.002) in RE, which was considered 'possibly beneficial'. Perceived readiness to perform was also significantly higher following DJ (13.3%, ES: 0.62, p=0.041). Differences in TTE and other physiological variables were 'most likely trivial' (ES: <0.2). Individual responses were small, however a partial correlation revealed a moderate relationship (r=-0.55, p=0.028) between change in RE and CMJ height.

In conclusion, this programme of research has added to the body of knowledge in the area of ST for distance runners by evaluating the evidence for its use, describing current practices, and examining the acute and chronic efficacy in adolescent distance runners. TT performance, RE and anaerobic capabilities are all likely to improve by including 2 or 3 sessions per week of ST for a 6-14 week period. This thesis demonstrated that it is possible that these improvements in RE and maximal sprint speed also extend to the post-pubertal adolescent age-group. Despite the advantages of supplementing a distance runners training routine with S&C, RT and PT are performed by approximately two-thirds and one-third of competitive distance runners respectively. It appears that younger runners, middle-distance specialists and runners of a higher competitive qualification are more likely to participate in ST. Finally, this thesis also provided novel insight into the use of strength-based exercise in the warm-up routine of a distance runner by showing that an acute episode of high-intensity plyometrics is capable of potentiating RE and enhancing perception of readiness to perform.

8.2 Practical Applications

The studies that comprise this thesis have a high level of applicability to practitioners who contribute to optimising the physical preparation of distance runners. Based upon the results of the systematic review (Study 1) and the training intervention (Study 4), it is likely that the addition of 2 or 3 supervised ST sessions per week will provide a sufficient stimulus to augment physiological parameters to a small extent within a ten week period. Benefits are likely to be larger for interventions of a longer duration and for ST programmes that are supervised by qualified practitioners. Although the majority of previous studies supplement a runners training with ST, there also appears to be no disadvantage to reducing weekly running volume to accommodate the addition of two weekly ST sessions. A variety of ST modalities can be used to achieve similar outcomes assuming runners are of a non-strength trained status, however to maximise long-term adaptations, it is suggested that a periodised approach is adopted with HRT prioritised initially (Beattie et al., 2017; Cormie et al., 2010b). Although changes in fat-free mass appear to be minimal, a targeted RT programme, that aims to increase muscle mass specifically around the proximal region of the lower limb may enhance biomechanical and physiological factors, which positively influence RE (Fletcher and MacIntosh, 2017).

Figure 8.1 provides an overview of the session design and training units used in the intervention study (Study 4). A similar session deign framework has also been used in other investigations (Beattie et al., 2017; Giovanelli et al., 2017; Mikkola et al., 2007), therefore it is proposed that this range of activities is suitable for a young athlete or distance runners embarking upon a S&C programme for the first time. Although not investigated specifically within this thesis, the inclusion of 'neuromuscular training' in the routine of distance runners is likely to reduce long-term injury risk (Lauersen et al., 2014; Leppänen et al., 2014; Myer et al., 2011; Steib et al., 2017), therefore it would be imprudent to omit this form of conditioning from these recommendations. The training intervention (Study 4) utilised a warm-up which included a series of bodyweight exercises designed to enhance movement skill and mobility. These activities form an important component of neuromuscular training, which should also encompass balance and dynamic stability exercises, speed training and strength work (Fort-Vanmeerhaeghe et al., 2016).

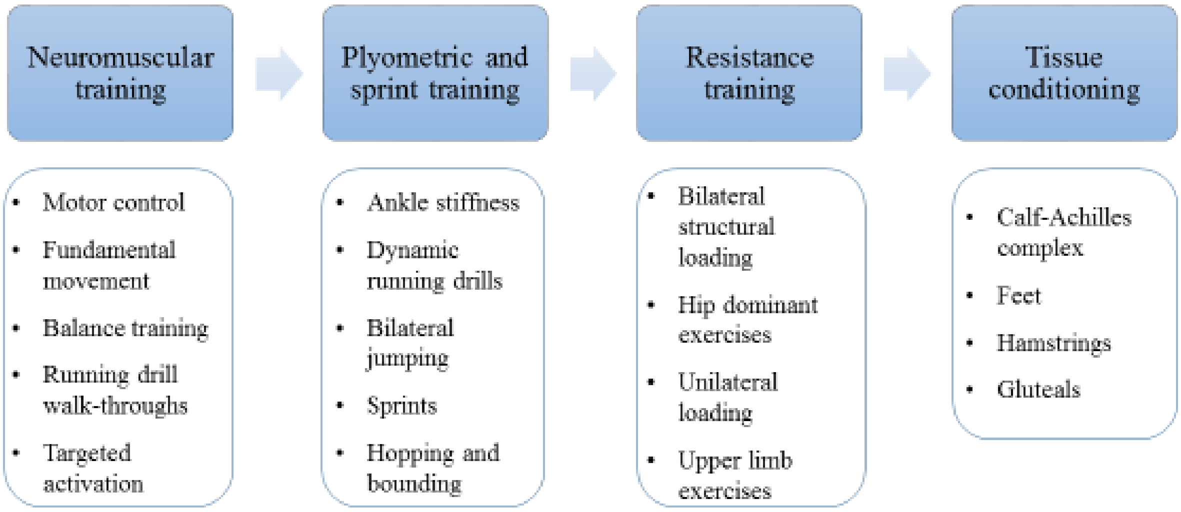


Figure 8.1. Recommended structure of a strength and conditioning session for adolescent distance runners, and runners new to these modalities of training.

Low intensity plyometric-based exercise, such as skipping, low-box DJ, mini hurdle jumps and short range hopping tasks, offer a potent stimulus to the neuromuscular system and have independently been shown to enhance RE and TT performance (Berryman et al., 2010; Pellegrino et al., 2016; Ramirez-Campillo et al., 2014; Spurrs et al., 2003; Turner et al., 2003). It is suggested that 30-60 foot contacts per session are utilised initially with novice-level distance runners. SpT has also been used in several investigations showing enhancements in performance-related factors (Millet et al., 2007; Paavolainen et al., 1999a; Skovgaard et al., 2014), and is likely to have contributed to the improvements observed in maximal sprint speed in Study 4.

RT, which should include both ERT and HRT, increases motor unit recruitment and firing frequency, thus enhances a runners ability to appropriately control and express force during ground contact. Exercises, such as squats, deadlifts, step-ups and lunge patterns, which possess similar kinematic characteristics to running gait, are likely to provide the greatest transfer (Bazyler et al., 2015) and were utilised in many of the works reviewed in Study 1 (Beattie et al., 2017; Giovanelli et al., 2017; Johnston et al., 1997; Piacentini et al., 2013; Storen et al., 2008; Skovgaard et al., 2014). Loaded jump squats, medicine ball throwing and weightlifting exercises are examples of suitable ERT exercises (Bazyler et al., 2015; Beattie et al., 2017; Cormie et al., 2011; Millet et al., 2002). Upper limb exercises such as press-ups, rowing exercises and overhead presses, should also be incorporated to offset the vertical angular momentum created by the lower limbs and aid in controlling excessive rotation forces (Johnston et al., 1997; Piacentini et al., 2013; Schumann et al., 2015). One to three sets of each exercise performed in a moderate repetition range (8-15 repetitions) is likely to provide non-strength trained individuals with a stimulus sufficient to drive neuromuscular adaptation whilst developing skill in each exercise (Beattie et al., 2017; Damasceno et al., 2015; Giovanelli et al., 2017; Millet et al., 2002; Saunders et al., 2004). Higher loads (≥80% 1RM) and lower repetition ranges (3-

8 repetitions) are likely to be required to provide further overload in more experienced athletes, with volume of work moderated via an increase in sets (Beattie et al., 2017; Mikkola et al., 2007; Piacentini et al., 2013; Skovgaard et al., 2014; Storen et al., 2008; Vikmoen et al., 2016).

The results of Study 2 showed that the most common reason for participation in S&C was reduction in injury risk (see Figure 4.3). Injury usually occurs over multiple running sessions when structure specific cumulative load exceeds capacity (Bertelsen et al., 2017). Youth endurance athletes have been identified as a high-risk group due to the rigorous training that they undertake during a critical period of their physical and emotional development (Matos and Winsley, 2007; Solomon et al., 2017). Neuromuscular training, PT and resistance-based exercises are likely to contribute towards lowering risk of injury via enhancements in motor control, and increases in bone mineral density and tissue resilience (Lauersen et al., 2014; Markovic and Mikulic, 2010; Myer et al., 2011; Warden et al., 2014). Exercises designed to expose specific muscles or tissues to a high magnitude of load are also likely to provide benefits to tendon stiffness (Fletcher et al., 2010) and tolerance to repetitive stress (Baar, 2017; Bohm et al., 2015; Mucha et al., 2017; Shield and Bourne, 2017; Tenforde et al., 2016; Warden et al., 2014). It is recommended that such exercises are positioned in final part of a session or performed separately as pre-fatiguing muscles in isolation is likely to be detrimental to performance in multi-joint tasks (Augustsson et al., 2003). Specifically for distance runners, targeted conditioning exercises should focus on the specific structures which are vulnerable to injury, or the muscles that contribute towards controlling the positioning of joints within the lower limb, such as: the intrinsic joints of the feet, the calf-Achilles complex, gluteal and hamstring muscles (Aderem and Louw, 2015; Duffey et al., 2000; Franettovich et al., 2014; McKeon and Fourchet, 2015; Messier et al., 1995; Mucha et al., 2017).

The findings of Study 2 identified that the most commonly utilised S&C training activities were stretching and core stability despite limited evidence that use of these modalities enhance performance or reduce injury risk. This underscores the need for practitioners working with distance runners to critically appraise the training activities they prescribe, and endeavour to educate their athletes on the methods which are most likely to reap the greatest benefits, such as RT and PT. Although the relatively high participation in some S&C activities is an encouraging finding, there were still many participants who lacked engagement, therefore there is a need for governing bodies and running organisations to improve their programmes of education and outreach efforts. The results of Study 2 should also be used by coaches to illustrate the extent to which elite runners engage with various S&C modalities, as this may have been a factor which contributed towards their success (Young and Salmela, 2010). Younger (under-20) runners, international competitors and middle-distance specialists were most likely to engage in ST activities, however coaches need to be aware that distance runners of all ages, abilities and specialisms can also benefit from these activities.

Results of Study 5 show that the inclusion of a set of six DJ in the warm-up routine of a well-trained middle-distance runners is likely to provide a moderate improvement in RE and an improved perception of readiness to perform. It is therefore advised that runners experiment with plyometric-based exercise prior to ‘tempo’ training runs, which are performed at a pace around sLTP. DJ can be performed in a field-based setting using a step or bench which approximates maximal CMJ height. Acute potentiation protocols (e.g. DJ, loaded back-squats and weighted vest sprints) are also a time efficient strategy to ensure ST is included in the programme of distance runners. If LCA are utilised in high frequency (4-6 times per week), this may also promote chronic neuromuscular adaptations, which may benefit RE and performance long-term. Further research is required to establish if this is indeed possible.

Exercise physiologists can be confident that measurement of important physiological determinants of distance running performance are highly-reproducible in competitive junior runners. However practitioners should be more cautious when using Borg’s RPE scale and interpreting absolute changes in BL and HR, as these are more liable to fluctuate from day-to-day. Similarly, maximal speed, when assessed with a flying start over 20 m, and squat jump height both possess high levels of inter-session stability. Practitioners should be aware that kinetic variables associated with maximal strength and explosive strength are prone to higher levels of error, thus young athletes may need several familiarisation sessions before valid measurements can be taken.

8.3 Main Limitations of Findings

There are a number of limitations associated with each study that have been discussed within respective Chapters. However it is important to highlight the main limitations of the findings from this thesis.

Studies 4 and 5 assessed the chronic and acute responses to a strength-based exercise intervention in adolescent distance runners. The laboratory measurements taken in these experiments predominantly assessed key physiological determinants and no direct performance-based measurements were utilised, thus reducing the external validity of findings. Although physiological variables such as $\dot{V}O_{2max}$, sFBLC and RE are capable of explaining a high proportion of inter-individual variability in middle- and long-distance running performance (Ingham et al., 2008; McLaughlin et al., 2010), it cannot be certain that an improvement in any one of these parameters will infer an improvement in race or TT performance. TTE at s$\dot{V}O_{2max}$, which is considered a proxy measure of performance, was used in Study 5, however a TTE test does not require a pacing strategy, which is an inherent component of real performance (Jeukendrup and Currell, 2005). It is also thought that TTE tests are influenced by fatigue, boredom and motivation, rendering them less reliable compared to a TT (Laursen et al., 2007).

A second practical limitation related to the strength-based exercise recommendations (Section 8.2) from this thesis is the assumption that distance runners are able to gain access to the equipment required to perform the exercises suggested. Many training activities, such as PT and bodyweight resistance exercises, can be performed without the need to access an S&C facility. However, the majority of exercises utilised in the studies reviewed (Study 1) and during the training intervention (Study 4) require the use of specialist equipment and qualified coaching support.

There are several examples within this thesis where participants were required to complete self-report questionnaires, which were subsequently used in data analysis or reporting of participant characteristics: S&C habits survey (Study 2; Appendix F), training log-book (Study 4; Appendix G) and pre-participation questionnaire (Study 4; Appendix B). The limitations of self-reporting physical activity behaviours are well-documented (Matthews, 2002; Sallis and Saelens, 2000). Specifically, re-call bias, honesty, incorrect interpretation of questions and a misunderstanding of ambiguous terms are all potential sources of error. Measures were taken to minimise the likelihood of these issues effecting results, such as a low Flesch readability score in the survey and providing verbal explanations to participants prior to completion of training logs. Despite these measures, the possibility that data were influenced by these sources of error cannot be discounted.

A number of measurements taken in this thesis were confounded by differences in body size, thus it was necessary to scale each of these variables appropriately to enable valid comparisons to be made. The allometric scaling values were derived from relatively small sample sizes (n=33-42) in homogenous groups of young distance runners, therefore this may have generated imprecise exponents due to sampling error. As previously discussed, the scaling exponents obtained are similar to estimations from previous studies (Folland et al., 2008a; Ingham et al., 2008; Jaric et al., 2002; Lolli et al., 2017), therefore any error which exists, is likely to be minimal. It is also recommended that fat-free mass is a more appropriate scaling denominator compared to whole body mass (Folland et al., 2008a; Lolli et al., 2017). Data were scaled to body mass in the present thesis, as fat-free-mass could only be estimated from a sum of skinfolds equation, which would have induced a further source of error. Obtaining a more valid estimation of each participants fat-free mass via bioelectrical impendence or air displacement plethysmography would enable a more accurate scaling factor to be derived.

Finally, although the findings of this thesis have a high level of practical application, no measurements were taken that allow for mechanistic insight into the results obtained. The potential mechanisms which underlie the improvements seen in performance, RE and anaerobic factors were discussed briefly as part of Study 1 (Section 2.5.4.9) and are largely based upon measurements of tendon and leg stiffness, running kinematics and EMG. Study 4 found a small (ES: 0.31-0.51) and possibly beneficial effect for RE and a very likely benefit to maximal speed following ten weeks of ST, however the reasons for these results can only be inferred from the strength-related outcome measures. Similarly, a set of DJ produced a moderate (ES: 0.67) acute benefit to RE, which was accompanied by a significant increase (ES: 0.62, p<0.05) in perceived readiness. This suggests that the mechanism of effect, could in-part, be centrally-derived, however without more sophisticated mechanistic measurement, this is simply conjecture. Study 2 described trends in S&C participation amongst a group of competitive distance runners, however the sources of motivation and reasons for the behaviours reported are also largely unknown.

8.4 Future Research Directions

This results of this thesis have made a meaningful contribution to the literature surrounding the use of strength-based exercise for distance runners, however a number of avenues for further research have been identified.

Each of the works reviewed in the systematic review (Study 1) lasted 14 weeks or less, with the exception of one, which was 40 weeks in duration (Beattie et al., 2017). Although ST is likely to provide a small-moderate benefit following a 2-3 month intervention, it is uncertain whether improvements in RE and performance continue to be meaningful beyond this period. It is unlikely that improvements would continue in a linear fashion, therefore it would be of interest to establish the extent to which ST could contribute towards the long-term enhancement of RE. In the study by Beattie and co-workers (2017), improvements in RE plateaued beyond the first 20 weeks of the intervention period, however this was likely due to a reduction in ST volume (2 sessions reduced to 1 session per week). $s\dot{V}O_{2max}$ did however continue to improve between 20-40 weeks, showing that improvements can still be made longer term, using only a single bout of ST exercise each week. This same finding was also observed for maximum aerobic power output in a group of well-trained cyclists who completed 25 weeks of ST split into a 12 week preparatory period (two weekly ST sessions) and 12 weeks competition (one weekly ST session) (Ronnestad et al., 2010). It is currently unknown what effect a twice weekly regimen of ST would produce over a period of longer than 20 weeks.

Although the interference phenomenon is likely to blunt strength adaptations observed in distance runners, the extent to which this occurs is currently uncertain due to the absence of a strength-only training group in the works reviewed. For longer term interventions, where improvements inevitably plateau, minimising attenuation of strength outcomes (and equally augmenting aerobic adaptation) potentially becomes more important. Therefore the organisation of ST around running training provides an avenue for further investigation. Similarly, it would be useful for practitioners to understand the optimal sequencing of ST modalities within a long-term programme in order to optimise training outcomes and facilitate a peaking response.

This thesis placed a focus on young distance runners in Study 4, however very few investigations have examined the effect of ST on other specific populations of runners such as female only

(Johnston et al., 1997; Vikmoen et al., 2016; Vikmoen et al., 2017), runners with a physical impairment, and masters age (Piacentini et al., 2013) competitors, therefore future research should attempt to address this shortage in literature.

Given the dearth of literature in the area of strength-based potentiation exercise for endurance athletes, there is scope for a future research to address a number of important questions concerning the efficacy of PAP protocols in middle- and long-distance runners (see Figure 2.8). There is good evidence for including high-intensity sprints to enhance $\dot{V}O_2$ kinetics, however a PAP-inducing LCA may also benefit the initial stages of performance via different mechanisms. It is unknown whether a combination of these approaches (priming and LCA) would augment performance to an even greater extent, or in fact produce excessive fatigue that attenuates performance. There is also a need to further explore the value of different LCA's including heavy resistance exercise, plyometrics and loading of the sport-skill itself. The findings of Study 5 suggest a possible acute benefit of plyometric-based exercise to RE, therefore the optimal prescription to maximise this potentiation response should also be investigated. It also appears that a LCA may only provide a performance advantage during the first few minutes of exercise, however it is currently unknown whether this effect could be longer lasting, or whether other determinants of performance are also affected favourably.

Distance runners mainly engaged with S&C activities to lower the risk of injury (63.1%), thus future research could consider how various S&C practices may contribute to this outcome. Addressing this question directly is challenging due to the complexity surrounding injury occurrence and the requirement for long-term prospective investigation using a large cohort. The change in maximal force producing capability was significantly greater (p<0.05, ES: 0.86) in the STG compared to the CG in the ten week ST intervention study (Study 4). Although not explored as part of this thesis, deficiencies in strength capabilities, particularly in the musculature around the hips, may be associated with risk of overuse injury in runners (Franettovich et al., 2014; Mucha et al., 2017; Peters and Tyson, 2013; Snyder et al., 2009; Steib et al., 2017). For young distance runners, who are likely to increase their training volume as they approach adulthood (Matos and Winsley, 2007), this potentially has more important implications than the performance-related factors studied in this thesis. The potential for ST to offset the risk of injury in young distance runners long-term therefore represents an interesting possibility for future research.

Although the survey results highlight the importance distance runners place on remaining injury free, over half (53.8%) of those who include S&C activities do so to improve their performance. Stretching (86.2%) and core stability exercises (70.2%) were identified as the most common S&C activities utilised, however these modalities of training have been researched extensively, both in terms of a means of enhancing performance and reducing injury risk (Baxter et al., 2017; Leppänen et al., 2014; Small et al., 2008; Wirth et al., 2017). Despite a fairly large body of evidence indicating the value of ST for performance-related outcomes, less than two-thirds (62.5%) of runners include RT and approximately one-third (35.1%) incorporate PT. Future research could therefore investigate the barriers to participation in S&C for sub-groups (club-standard and masters runners) to assist coaches and organisations with developing initiatives to improve engagement.

CHAPTER 9

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APPENDIX A

ETHICAL APPROVAL LETTERS FOR EXPERIMENTAL STUDIES

Richard Blagrove (SHAS): ‘Strength and conditioning habits of distance runners’.

7 April 2016

Dear Richard

University Ethics Sub-Committee

Thank you for submitting your ethics application for the above research.

I can confirm that your application has been considered by the Ethics Sub-Committee and that ethical approval is granted.

Yours sincerely

Dr Conor Gissane
Chair of the Ethics Sub-Committee

Richard Blagrove (SHAS): 'The reliability of physiology and strength metrics in adolescent distance runners' (amendments to a previously approved research)

17 May 2016

Dear Richard

University Ethics Sub-Committee

Thank you for submitting your ethics application for the above research.

I can confirm that your application has been considered by the Ethics Sub-Committee and that ethical approval is granted.

Yours sincerely

Dr Conor Gissane
Chair of the Ethics Sub-Committee

Cc Nick Clark/ Conor Gissane

Richard Blagrove (SHAS) Effect of a resistance training intervention on strength and performance measures in adolescent endurance runners'.

1st September 2015

Dear Richard,

University Ethics Sub-Committee

Further to your request to include an additional question to your original ethics application, I can confirm that I have approved this via Chair's action and you have ethical approval to undertake the research.

Yours sincerely

Dr Conor Gissane
Chair of the Ethics Sub-Committee

10 May 2016 Unique Ref: SMEC_2015-16_56

Richard Blagrove & Kristina Powell (SHAS): ‘The acute effect of depth jumps on the running physiology of young distance runners.’

Dear Richard and Kristina

University Ethics Sub-Committee

Thank you for submitting your ethics application for the above research.

I can confirm that your application has been considered by the Ethics Sub-Committee and that ethical approval is granted.

Yours sincerely

Conor Gissane

Dr Conor Gissane
Chair of the Ethics Sub-Committee

APPENDIX B

PRE-PARTICIPATION QUESTIONNAIRE

Pre-Participation Questionnaire

Please complete the following personal details as accurately as possible:

Name		
Date of birth		
Email address		
Telephone number		
Athletics club		
Years of competitive experience in athletics		
What strength training do you currently perform as part of your training (if any)?		
Main competitive track distance		
Personal best times and date achieved	800m:	Date (month and year):
	1500m:	Date (month and year):
	3000m:	Date (month and year):
	5000m:	Date (month and year):
	Others (eg steeplechase):	Date (month and year):
Dominant hand/foot?	Right / Left	
Any current injuries or injuries in the last month that may prevent you participating in exercise?		

APPENDIX C

EXAMPLE INFORMED CONSENT

Parent/Guardian Consent Form

Name of Participant (your son/daughter): ____

Title of the project: *Effect of a resistance training intervention on performance of adolescent endurance runners*

Main investigator and contact details: Richard Blagrove; Telephone number – 0208 240 4224; Email – richard.blagrove@stmarys.ac.uk

1. I agree to my son/daughter taking part in the above research. I have read the Participant Information Sheet, which is attached to this form. I understand what is required of my son/daughter during the research, and all my questions have been answered to my satisfaction.
2. I understand that I am free to withdraw my son/daughter from the research at any time, for any reason and without prejudice.
3. I have been informed that the confidentiality of the information I, and my son/daughter provides, will be safeguarded.
4. I am free to ask any questions at any time before and during the study.
5. I have been provided with a copy of this form and the Participant Information Sheet.

Data Protection: I agree to the University processing personal data, which I have supplied. I agree to the processing of such data for any purposes connected with the Research Project as outlined to me.

Name of parent/guardian (print)……………………….. Signed…………………..……Date……………

Name of witness (print)……………………………Signed……………….…….Date……………….

If you wish to withdraw the participant from the research, please complete the form below and return to the main investigator named above.

Title of Project: *Effect of a resistance training intervention on performance of adolescent endurance runners*

I WISH TO WITHDRAW MY SON/DAUGHTER FROM THIS STUDY

Name: ____

Signed: ______________________________ Date: ___________________

APPENDIX D

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

SCHOOL OF SPORT, HEALTH AND APPLIED SCIENCE
CONFIDENTIAL MEDICAL HISTORY / PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q) FORM

This screening form must be used in conjunction with and agreed Consent Form.

Full Name:		Date of Birth:	
Height (cm):		Weight (kg):	

Have you ever suffered from any of the following medical conditions? If yes please give details:

	Yes	No	Details
Heart Disease or attack	☐	☐	______________________
High or low blood pressure	☐	☐	______________________
Stroke	☐	☐	______________________
Cancer	☐	☐	______________________
Diabetes	☐	☐	______________________
Asthma	☐	☐	______________________
High cholesterol	☐	☐	______________________
Epilepsy	☐	☐	______________________
Allergies	☐	☐	______________________
Other, please give details	☐	☐	______________________

Do you suffer from any blood borne diseases? If yes please give details;

Please give details of any **medication** you are currently taking or have taken regularly within the last year:

Please give details of any **musculoskeletal injuries** you have had in the **past 6 months** which have affected your capacity to exercise or caused you to take time off work or seek medical advice:

Other Important Information

During a typical week approximately how many hours would you spend exercising?

If you **smoke** please indicate how many per day:

If you drink **alcohol** please indicate how many units per week:

Are you currently taking any **supplements or medication?** Please give details:

Is there any other reason that is not prompted by the above that would prevent you from participating within the relevant activity?

Signature (Participant):		**Date:**	
Signature (Test Coordinator*):		**Date:**	

**Test coordinator: The individual responsible for administering the test(s)/session and subsequent data collection*

APPENDIX E

PHYSIOLOGY AND BIOMECHANICS TESTING DATA RECORDING SHEETS

Data Collection Sheet - Physiology Testing

Trial identification Baseline / Follow-up

Name	
Date and Time	
DOB	
PARQ	
Informed consent	
Personal info sheet	

1. Ambient Conditions

Barometric Pressure	
Temp.	
Humidity	

2. Anthropometrics

Weight	kg	kg
Standing height	cm	cm
Sitting height	cm	cm

2b. Skinfolds

Tricep	mm	mm	mm
Bicep	mm	mm	mm
Subscapula	mm	mm	mm
Suprailiac	mm	mm	mm

Lactate Profile 3 min/stage; 30s rest between stage. >4mmol/L

Warm-up speed (5 min) km/h

Stage	REST	1	2	3	4	5	6	Mask type/size
Real Time								
Speed (km/h)*								
HR (last 30s) 1	bpm							
HR (last 30s) 2	bpm							
HR (last 30s) 3	bpm							
RPE (last 30s)								
Lactate 1								
Lactate 2								

VO2max. Test Start from speed that elicits approx 4mmol/L. Increase 1% every minute to exhaustion

Start time	
End time	
Speed	
Gradient at max	
HRmax	
RER	
Lactate 1	
Lactate 2	
VO2peak	

Data Collection Sheet - Strength Testing	
Name	
Date and Time	
DOB	
Trial identification	Familiarisation / Baseline 1 / Baseline 2 / Follow-up
PARQ	
Informed consent	
Personal info sheet	
1. 3 min jog w/u	
2. 20m sprint	
Tester	
Trial 1	
Trial 2	
Trial 3	
3a. Squat jump	
Tester	
Files saved as	
4. Isometric squat	
Tester	
Squat stand hole	
Chain link	
Files saved as	

APPENDIX F

SURVEY – STRENGTH AND CONDITIONING HABITS OF DISTANCE RUNNERS (STUDY 2)

Strength and Conditioning Habits of Runners

Section 1: Introduction

Thank you for agreeing to fill out our survey on the strength and conditioning (S&C) habits of distance runners. Lots of runners of all ages and standards are recognising the benefits of S&C, but little is known about how this type of training is being used. Whether you use S&C exercises or not, your views on this topic are important to us. The purpose of this survey is to find out which types of runners are using S&C and the sorts of exercises which are popular. We are also interested in where runners get their advice on S&C and whether anything can be done to improve the information that is available.

The survey should take 10-15 minutes to complete but you can expand on any answers at the end of the survey. Your answers will be completely anonymous so please respond to the questions as accurately and honestly as possible. If you have any questions about the survey or S&C, please email: richard.blagrove@stmarys.ac.uk.

Statement of consent

By completing this survey I understand that my responses will be used for research purposes only and I will not be named. I am over the age of 18 and consider running to be my main sport or physical pastime. If I am under 18 years old I have obtained a signature from my parent/guardian (below) providing permission for me to complete the survey.

(*please tick one option*):

I agree

I disagree (*please discontinue the survey*)

Signature of parent/guardian (for runners aged under-18):

____

Section 2: General Information

1. What is your sex? (*tick one option only*)

   Male
   Female

2. What age group are you in? (*tick one option only*)

   Under-17
   Under-20
   Under-23
   Senior
   Veteran 40-49
   Veteran 50-59
   Veteran 60+

3. What events do you usually run or compete in? (*tick one option only*)

   Middle distance (800m-3000m)
   Long-distance (5000m-Half marathon)
   Marathon
   Ultra-distance
   Fell or trail running

4. What level do you currently compete at? (*tick one option only*)

   I only participate and don't compete
   Local for club/school/University
   County
   Regional
   National
   International

Section 3: Running Training

5. How many times do you run per week? (*tick one option only*)

   1-2
   3-4
   5-6
   7-8
   9-10
   11 or more

6. How many miles do you usually run each week? (*tick one option only*)

   <20 miles (32km)
   21-40 miles (32 – 64km)
   41-60 miles (65 – 96km)
   61-80 miles (97 – 128km)
   81-100 miles (129 – 160km)
   >100 miles (160km)

7. How many times per week do you usually perform interval training or high-intensity running (including 'tempo' runs)? (*tick one option only*)

   0
   1-2
   3-4
   5 or more

8. How many injuries (which have stopped you from running for 5 days or more) have you had in the last 2 years? (*tick one option only*)

   0
   1
   2
   3
   4
   5 or more

Section 4: Strength and Conditioning

9. On a scale of 1-4, how beneficial do you believe the following activities are for a runner? (*tick one box only for each activity*)

	1 Not beneficial	2 Slightly beneficial	3 Beneficial	4 Highly beneficial
Resistance training (barbells, dumbbells, medicine balls, resistance machines)				
Plyometrics (e.g. jumping, hopping, bounding)				
Fundamental movement skills (e.g. squat, lunge, step-up)				
Running technique drills				
Bodyweight exercises (e.g. press-ups, pull-ups, single leg squat)				
Circuit training				
Stretching				
Foam rolling				
Balance training (including unstable surface training)				
Core stability (abdominal exercises)				
Barefoot exercises				

10. Do you have any of these concerns about how strength and conditioning may impact your running? (*tick all options that apply*)

I don't know the best exercises or how to do them
I will put on unwanted muscle bulk
It will leave my muscles feeling sore and stiff
It will make me tired for my running sessions
It will take up valuable training time that could be spent running
None of the activities will benefit my running
Some of the activities may cause an injury
Lifting weights isn't safe or appropriate at my age
No, I don't have any of these concerns
Other (please specify)

11. What tests (if any) do you perform when assessing your fitness? (*tick all options that apply*)

I don’t perform any tests
Movement screening
Jump tests
Sprint tests
Maximum strength tests
Muscular endurance tests
Flexibility tests
Other (please specify)

12. On a typical week, do you use the following activities in your training schedule, and if so how often, for how long and when do you usually do them? (*tick one box only for each activity*)

	Do you use the following activities? * Yes/No	If yes, how often do you do this activity each week? 1-2; 3-4; 5-6; 7 or more	If yes, how long do you spend on the activity per session? Less than 15 min; 15-30 min; 30-45 min; 45-60 min; More than 60 min	If yes, when do you usually do the activity? During a warm-up for a running session; After a running session; As an independent session; As part of a S&C session (with other activity/activities)
Resistance training (barbells, dumbbells, medicine balls, resistance machines)				
Plyometrics (e.g. jumping, hopping, bounding)				
Fundamental movement skills (e.g. squat, lunge, step-up)				
Running technique drills				
Bodyweight exercises (e.g. press-ups, pull-ups, single leg squat)				
Circuit training				
Stretching				
Foam rolling				
Balance training (including unstable surface training)				
Core stability (abdominal exercises)				
Barefoot exercises				

13. Where do you typically perform your exercises? *(tick all options that apply)*

At home
Gym
Indoor athletics track or sports hall
Outdoor athletics track
A park
Other (please specify)

14. If you include strength and conditioning exercises as part of your training, why is this? (*tick all options that apply*)

Not sure
I am told to

Improve my performance
Lowers my risk of getting injured
Rehabilitation from an injury
Improves my running technique
It is fun and enjoyable
Improve my body image
Other (please specify)

Section 5: Coaching

15. Where do you get information on the best exercises and correct way to do them? (*tick all options that apply*)

    A qualified strength and conditioning coach
    An unqualified strength and conditioning coach
    Personal trainer/gym instructor
    Running coach
    Physiotherapist
    Parent/guardian
    A friend/club mate
    Internet sites
    Books
    Magazines
    Journals
    Other (please specify)

16. Who coaches you when you do your strength and conditioning exercises? (*tick all options that apply*)

    I don't receive any coaching
    Strength and conditioning coach
    Personal trainer/gym instructor
    Physiotherapist
    Running coach
    Parent/guardian
    A friend/club mate

17. Would you like more advice on the following activities? (*tick one box only for each activity*)

	No thanks	I have a good coach or know a lot already	No thanks, I am not interested	Maybe on some aspects	Yes
Resistance training (barbells, dumbbells, medicine balls, resistance machines)					
Plyometrics (e.g. jumping, hopping, bounding)					
Fundamental movement skills (e.g. squat, lunge, step-up)					
Running technique drills					
Bodyweight exercises (e.g. press-ups, pull-ups, single leg squat)					
Circuit training					
Stretching					
Foam rolling					
Balance training (including unstable surface training)					
Core stability (abdominal exercises)					
Barefoot exercises					

18. Do you know how to obtain professional advice on strength and conditioning for runners? (*tick one option only*)

Yes

If yes, where?

No

19. Do you have any other opinions about S&C or detail about your S&C programme which you wish to share?

Section 6: All done!

Thank you for taking the time to complete our survey!

If you have any questions about the survey or strength and conditioning for runners, please contact richard.blagrove@stmarys.ac.uk

APPENDIX G

TRAINING LOG FOR PARTICIPANTS IN TRAINING INTERVENTION (STUDY 4)

Training Log

It is important that your daily training is logged accurately and returned each week. Please complete the following boxes each day as accurately as possible providing as much detail as you can.

Name: ____

Week beginning date: ______________________________

Day	Training Session	Time/Pace	Total Distance	On a scale of 1-10 how hard was this session? (1 = very easy; 10 = exhausting)	Other notes (including any injuries)
Monday					
Tuesday					
Wednesday					
Thursday					
Friday					
Saturday					
Sunday					