

Strategies to Improve Running Economy in Trained Distance Runners

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ABSTRACT

Running economy is considered an important physiological measure for endurance athletes, especially distance runners. Of the numerous metabolic, cardiopulmonary, biomechanical and neuromuscular characteristics contributing to running economy, it seems that few are subject to alteration or improvement through training or other interventions. Over the past decade, various strategies to improve running economy have been investigated, but the evidence supporting different forms of movement-specific resistance exercises is limited and conflicting. Furthermore, there is a paucity of data evaluating the subsequent effects of changes in running economy on actual running performance. Given a range of mechanisms have been described as mediators to explain changes in running economy (Chapter 2) following various training strategies (Chapter 3) the initial aim of this thesis was to describe the determinants of running economy in a population analogous to that of which would participate in the ensuing experimental studies (Chapter 4). To determine factors and to assess the efficacy of different movement-specific resistance strategies to improve running economy and running performance, one descriptive and three experimental studies were conducted with a variety of methodological approaches to address the main aim of this thesis: to examine the relative efficacy of different forms of movement-specific resistance exercise to improve running economy and performance in competitive distance runners.

The purpose of Chapter 4 was to evaluate the lower-body determinants of running economy among well-trained male and female distance runners. Leg stiffness ($r = -0.80$) and Achilles moment arm length ($r = 0.90$) had high to extremely high correlations with running economy and each other ($r = -0.82$), whereas correlations between running economy and kinetic measures (peak force, peak power and time to peak force) for both genders were unclear and biomechanical measures (stride rate, stride length, contact time, flight time) were small-moderate. At all common test velocities women were more economical than men (effect size (ES) = 0.40). The results of Chapter 4 suggested that while lower-body stiffness and Achilles moment-arm length were substantially related to the running economy of well-trained runners, no single lower-body measure could fully explain differences in running economy between individuals or genders. Running economy is therefore likely determined from the sum of influences from multiple lower-body attributes.

The purpose of Chapter 5 was to determine the acute effects of wearing a weighted vest during warm-up "strides" on running economy, neuromuscular

measures, and running performance. The weighted-vest condition resulted in a 6.0% improvement in running economy along with a 20% increase in leg stiffness, which resulted in a 2.9% enhancement in peak running speed. Relationships between change scores showed that changes in leg stiffness could explain all the improvements in performance and running economy. Results from study two showed that running economy and performance could be improved following a movement-specific form of resistance exercise.

Another common way runners obtain resistance to movement is various forms of uphill running. Consequently, Chapter 6 examined the optimum loading parameters to five different uphill interval-training programs. There was no clear optimum for time-trial performance, and the mean improvement across each training intensity was ~2.0%, however, the highest intensity was clearly optimal for running economy (improvement of 2.4%), and for all neuromuscular measures, whereas other aerobic measures were optimal near the middle intensities. These findings supported anecdotal reports for incorporating uphill interval training in the training programs of distance runners to improve running economy and other physiological parameters relevant to running performance.

The final part of this thesis focused on two forms of resistance training (heavy-resistance training and plyometric training), which each offer distinct physiological and neuromuscular adaptations that previously have been shown to enhance running economy on their own. Therefore the last experimental study (Chapter 7) examined the effects of combining these two modes of resistance training on running economy and competition performance in male and female cross-country runners. Results showed that heavy-resistance training produced small to moderate improvements in peak speed (male 3.4%, female 2.2%), running economy (male 1.5%, female 2.5%) and neuromuscular characteristics relative to plyometric resistance training, whereas changes in biomechanical measures favored plyometric resistance training. Overall, males made less absolute gains than females in most tests. Both treatments had possibly harmful effects on competition times in males ($0.5\% \pm 1.2\%$), but there may have been benefit for some individuals, whereas both treatments were likely beneficial for all females (-1.2% ; $\pm 1.3\%$), but heavy-resistance was possibly better than plyometric resistance training.

Overall, the findings from this thesis have demonstrated for the first time that well-trained distance runners can substantially (2 to 6%) improve their running economy through acute and chronic bouts of movement-specific resistance exercise, either by performing strides with a weighted vest or short-duration near-maximal uphill

sprints. Furthermore, it appears that heavy resistance-training is a superior training modality to the combination of heavy-resistance and plyometric training at enhancing running economy. Regardless of the exercise mode, improvements in running economy appear to be modulated through enhancements in lower-body stiffness, but other trainable and non-trainable factors may be related to and affect running economy. Moreover, it appears that the improvements in running economy following various training strategies presented in the thesis contribute to improved running performance.

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ETHICAL APPROVAL

Ethical approval for this thesis research was granted by the Auckland University of Technology Ethics Committee (AUTEC) and joint ethical approval for Chapter 4 was granted by AUTEC and the Hope College Human Subjects Review Board (HSRB). The AUTEC references were:

10/160 Strategies to improve running economy in New Zealand triathletes and runners. Approved on 3 August 2010.

13/153 Effects of warm-up with weighted vest on running economy and peak speed. Approved 8 July 2012.

The Hope College HSRB reference was:

A competition-based design to assess a resistance training intervention affecting the performance and running economy of cross-country runners.
Approved 10 August 2011.

ATTESTATION OF AUTHORSHIP

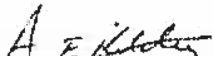
I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for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



Kyle Barnes

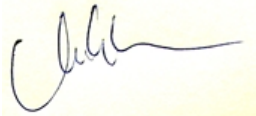
March 2014

Supervisor Signatures




Andrew Kilding

March 2014



Will Hopkins

March 2014



Mike McGuigan

March 2014

PUBLICATIONS AND CONFERENCE PRESENTATIONS ARISING FROM THIS THESIS

Chapters 2-7 of this thesis represent six separate papers that have been published or submitted to peer-reviewed journals for consideration for publication. These papers were prepared in collaboration with my supervisors Associate Professor Andrew Kilding, Professor Will Hopkins and Professor Mike McGuigan. Chapter 4 was also prepared in collaboration with Professor Mark Northuis of Hope College in Holland, Michigan USA. The percentage of work from each other is noted in brackets.

Conference presentations

Barnes, K. R., Hopkins, W. G., McGuigan, M. R., & Kilding, A. E. (2012). Effects of different uphill interval-training programs on running economy and performance. *Proceedings of Sports Medicine Australia conference 2012, 31 October – 3 November p 19.*

(Kyle Barnes 80%, Andrew Kilding 10%, Will Hopkins 8%, Michael McGuigan 2%)

Published peer-reviewed articles

Barnes, K. R., Hopkins, W. G., McGuigan, M. R., & Kilding, A. E. (2013). Effects of different uphill interval-training programs on running economy and performance. *International Journal of Sports Physiology and Performance*; 8(6), 639-647.

(Kyle Barnes 80%, Andrew Kilding 10%, Will Hopkins 8%, Michael McGuigan 2%)

Barnes, K. R., Hopkins, W. G., McGuigan, M. R., Northuis, M. E., & Kilding, A. E. (in press). Effects of resistance training on running economy and cross-country performance. *Medicine and Science in Sports and Exercise.*

(Kyle Barnes 80%, Will Hopkins 10%, Andrew Kilding 5%, Michael McGuigan 3%, Mark Northuis 2%)

Barnes, K. R., Hopkins, W. G., McGuigan, M. R., & Kilding, A. E. (in press). Lower Limb Determinants of Running Economy in Male and Female Distance Runners. *Journal of Strength and Conditioning Research.*

(Kyle Barnes 80%, Andrew Kilding 15%, Michael McGuigan 5%)

Barnes, K. R., Hopkins, W. G., McGuigan, M. R., & Kilding, A. E. (in review). Warm-up with a weighted vest improves running performance via leg stiffness and running economy. *Journal of Science and Medicine in Sport.*

(Kyle Barnes 80%, Andrew Kilding 10%, Will Hopkins 5%, Michael McGuigan 5%)

Peer-reviewed articles currently under review

Barnes, K. R., Kilding, A. E. (in review at *Sports Medicine*). Running Economy: Measurement, Norms and Determining Factors.
(Kyle Barnes 85%, Andrew Kilding 15%)

Barnes, K. R., Kilding, A. E. (in preparation for submission to *Sports Medicine*). Strategies to Improve Running Economy.
(Kyle Barnes 85%, Andrew Kilding 15%)

DEDICATION

I wish to dedicate this thesis to the people who have always been there for me, my parents Rusty and Sandy Barnes, brother Casey, sister-in-law Jennifer, niece Kendall, and compass Danielle Tauro, for your support to pursue my dream and do it 12,000 km (~8,000 mi) from home. The completion of this thesis would not have been possible without your patience, understanding, love and support throughout the duration of this thesis. Thank you so much, I love you all.

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I am thankful for and would like to acknowledge many others who helped me along the way: my father and mother, whose love selflessly took me on this journey 8,000 miles from home and continually provided me with the support and encouragement to get where I am now; my brother, sister-in law and niece for their love (and sometimes tough love), encouragement, and helping shape who I am today; Danielle Tauro, my partner, thank you for reorienting my life, faithfully going through the latter part of the process with me, and making so many sacrifices for me; the Kilding family for being my home away from home, my friends for the many hours of Skype calls which allowed us to grow closer despite the distance; and my roommates and colleagues for many good times, adventures and bouncing ideas with me. This includes, but is not limited to Scott Brown, Erin Feldman, Sarah Manson, Cesar Meylan, Travis McMaster and Albert Chang.

I am beyond grateful to all of my participants who were not paid to participate in the project. The people who participated in my study were generous with their time in a way that I can never repay.

The path to becoming a Doctor is littered with distractions. I'd like to thank those distractions for making me the person I am.

Once a runner...

CHAPTER 1: INTRODUCTION

1.1 Thesis Rationale

In highly-trained runners, a number of physiological factors determine running performance, which include an athlete's maximal oxygen uptake (VO_{2max}), lactate threshold, fractional utilization of VO_{2max} and running economy (Costill, 1967; Costill, Thomason, & Roberts, 1973; Daniels, 1974a). Running economy is represented by the energy demand for a given velocity of submaximal running and expressed as the submaximal VO_2 at a given running speed (Conley & Krahenbuhl, 1980; Daniels, 1985; Saunders, Pyne, Telford, & Hawley, 2004a). Runners with good running economy use less oxygen than runners with poor running economy at the same steady-state speed (Daniels, 1985). A strong relationship has been demonstrated between running economy and endurance running performance in moderate to highly trained runners with a similar VO_{2max} (Costill et al., 1973; Morgan, Baldini, Martin, & Kohrt, 1989).

Coincidentally, at the onset of my doctoral program Triathlon New Zealand hired world-renowned running coach and physiologist Jack Daniels (Daniels, 1974a, 1974b, 1985, 1998; Daniels & Daniels, 1992; Daniels, Foster, Daniels, & Krahenbuhl, 1977; Daniels, Krahenbuhl, Foster, Gilbert, & Daniels, 1977; Daniels & Oldridge, 1970, 1971; Daniels, Oldridge, Nagle, & White, 1978; Daniels & Scardina, 1984; Daniels, Yarbrough, & Foster, 1978), to lead a run focus workshop aimed at uncovering ways of optimizing running performance. Interestingly, enhancing running economy arose as one of the main concluding action points generated from this workshop. This inspired me to consider novel ways of improving running economy in triathletes and runners alike. It is apparent within the literature that training can induce positive changes in running economy via a range of physiological and biomechanical adaptations (Bransford & Howley, 1977; Dolgener, 1982). However, during my examination of the literature I realized that evidence supporting different forms of movement-specific resistance training were limited and incomplete. Furthermore, there is a paucity of data evaluating the subsequent effects of changes in running economy on running performance. This led me to consider various resistance training methods to enhance running economy and performance; particularly movement-specific modes of resistance training that can be applied to runners in non-laboratory based training scenarios and the underlying mechanisms associated with the improvements. Training programs can potentially improve running economy through metabolic, cardiorespiratory, biomechanical and/or neuromuscular adaptations. Ultimately, any intervention that can reduce oxygen demand at a range of speeds would allow a runner to run faster over a given distance or to run longer at a constant speed because of the

reduced oxygen consumption. It follows any strategy to improve running economy could facilitate improved performance in distance runners. Accordingly, in response to the call for more research from Jack Daniels and in accordance with limitations in the literature, I proposed to conduct research that has the potential to guide coaching practice, by examining various movement specific strategies to improve running economy and performance in well-trained runners.

The primary focus of this thesis was to examine running economy as a multifactorial concept through various reviews, descriptive, acute and training studies, while employing a variety of methodological approaches with the aim of improving running economy and running performance. In part one (Chapter 2) of a two-part review a comprehensive examination of the current scientific knowledge regarding the ambiguity in the literature regarding how we define running economy was undertaken. To the layperson this measure is perceived as a simple concept, however this value reflects the metabolic, biomechanical, and neuromuscular components of running economy, without consideration for what portion of that VO_2 is a function of good or bad mechanics as opposed to being related to differences in metabolism or force production which may exist in different athletes or under different conditions (Anderson, 1996; Bonacci, Chapman, Blanch, & Vicenzino, 2009; Daniels, 1985; Saunders, Pyne, et al., 2004a). Additionally, it often gets overlooked that it is possible to become more economical in one area yet have running economy be negatively affected because of a larger decrease in another aspect of efficiency. Many of these factors affecting running economy represent specific or independent qualities of running economy and these qualities can be assessed and trained independently. It is apparent within the literature that trained runners have superior running economy to lesser-trained or untrained runners (Bransford & Howley, 1977; Daniels, Oldridge, et al., 1978; Dolgener, 1982), indicating positive adaptations in response to training programs (Beneke & Hutler, 2005). Therefore, in part two (Chapter 3) of our review series we examined various strategies to improve running economy and the mechanisms associated with these adaptations in response to training. Training programs can potentially improve running economy through metabolic, biomechanical and/or neuromuscular adaptations. Any intervention that can reduce oxygen demand at a range of speeds could also facilitate improved performance in distance runners and would certainly be welcomed by coaches, athletes and sports scientists.

Running economy has been identified as a critical factor contributing to distance running performance (Conley & Krahenbuhl, 1980; Conley, Krahenbuhl, Burkett, & Millar, 1984; Costill, 1967; Costill et al., 1973; Daniels, 1974a; Daniels & Daniels, 1992;

di Prampero et al., 1993; Jones, 2006; Pollock, 1977). Information in the literature suggests running economy can vary among runners with similar VO_2max by as much as 30% (Daniels, 1985). Runners with good running economy tend to run faster at a given distance or longer at a constant velocity than runners with poor running economy, assuming their VO_2max is the same. However, despite the performance benefits of being an economical runner, researchers have yet to resolve why some runners demonstrate markedly better economy when compared to counterparts exhibiting similar fitness, training history and performance backgrounds (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Daniels, Krahenbuhl, et al., 1977; Williams & Cavanagh, 1987). Recent research has focused on various biomechanical, anthropometric and/or neuromuscular characteristics as mechanisms to explain improvements in running economy (Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999; Paavolainen, Nummela, Rusko, & Hakkinen, 1999; Paavolainen, Nummela, & Rusko, 1999; Spurrs, Murphy, & Watsford, 2003). Therefore the focus of Chapter 4 was to evaluate the lower-body determinants of running economy among well-trained male and female distance runners. It was decided to use male and female runners as subjects since previous data has shown mixed findings concerning differences in running economy that exist between genders (Bransford & Howley, 1977; Daniels, Krahenbuhl, et al., 1977; Davies & Thompson, 1979; Maughan & Leiper, 1983; Morgan et al., 1995; Morgan & Craib, 1992). As a secondary focus, this study explored whether many of these lower-body characteristics can explain differences in running economy between male and female trained distance runners.

Prior warm-up activities are a widely accepted practice preceding nearly every athletic event to prepare the body for optimal competition performance (Bishop, 2003). An active warm up is probably the most widely used warm-up technique for distance runners because it is likely to induce specific metabolic and cardiovascular changes conducive to distance-running performance (Bishop, 2003). Recent research has focused on various warm-up or priming exercises that can alter oxygen uptake (VO_2) kinetic responses to subsequent high-intensity exercise and enhance performance (Bishop, Bonetti, & Dawson, 2001; Hajoglou et al., 2005; Ingham, Fudge, Pringle, & Jones, 2013). While different training regimens have demonstrated concomitant improvements in neuromuscular measures, running economy and distance running performance (Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003), to date no research has examined modifying these parameters acutely to improve distance-running performance. Therefore, for Study 4 we chose to examine the efficacy of acutely modifying various neuromuscular parameters and running economy to enhance running performance. To do this, we realized that we needed to precondition the

muscles in some way to enhance metabolic and neuromuscular efficiency. Post-activation potentiation is a well-recognized phenomenon that involves the preconditioning of muscle through heavy exercise and has previously demonstrated acute improvements in performance during sprinting and weightlifting activities (Hodgson, Docherty, & Robbins, 2005; Tillin & Bishop, 2009). A common method used by athletes to facilitate a post-activation potentiation response is performing sport specific movement patterns while wearing a weighted vest that provides additional resistance to movement. In track and field running events, athletes typically employ a warm-up procedure that includes low intensity jogging, mobilization exercises and short duration fast-running 'strides' (Ingham et al., 2013). By combining these two modes of training I realized that much like when baseball players add a weighted donut to the end of their bats during their warm-up swings in order to increase swing speed when the donut is removed, perhaps if runners add artificial weight to their torso during warm-up exercises (strides), when the weight is removed it may enhance running performance as well.

The final two investigations of this thesis are training studies aimed at chronically enhancing running economy in well-trained runners. For Chapter 5 we adopted a dose-response design to investigate the effects of various uphill interval-training programs on physiological and performance measures. Previous research has shown interval training at 93–120% velocity at VO_2 max (vVO_2 max) (Billat, Flechet, Petit, Muriaux, & Koralsztein, 1999; Franch, Madsen, Djurhuus, & Pedersen, 1998; Laffite, Mille-Hamard, Koralsztein, & Billat, 2003; Sjodin, Jacobs, & Svedenhag, 1982; Slawinski, Demarle, Koralsztein, & Billat, 2001) and continuous running at velocity at the onset of blood lactate accumulation ($vOBLA$) (Billat et al., 1999; Denadai, Ortiz, Greco, & de Mello, 2006; Sjodin et al., 1982) on level ground substantially improves running economy. However, despite coaches often utilizing various forms of hill training in periodized training programs for distance runners, only anecdotal reports (Kurz, Berg, Latin, & Degraw, 2000; Midgley, McNaughton, & Jones, 2007; Saunders, Pyne, et al., 2004a) and two research investigations (Ferley, Osborn, & Vukovich, 2012; Houston & Thomson, 1977) exist concerning the physiological responses and potential improvements in performance to such training. Therefore, in view of the uncertainty about the physiological effects of uphill training on distance running performance we adopted this modeling approach in an attempt to determine the most effective uphill interval-training protocol on running economy and performance.

Resistance training and plyometric training are two interventions that have been shown to improve running economy in recreational (Hickson, Dvorak, Gorostiaga,

Kurowski, & Foster, 1988; Taipale et al., 2009; Taipale, Mikkola, Vesterinen, Nummela, & Hakkinen, 2013; Turner, Owings, & Schwane, 2003), moderately trained (Albracht & Arampatzis, 2013; Barnes, Hopkins, McGuigan, Northuis, & Kilding, 2013; Berryman, Maurel, & Bosquet, 2010; Francesca et al., 2012; Guglielmo, Greco, & Denadai, 2009; Hamilton, Paton, & Hopkins, 2006; Johnston, Quinn, Kertzer, & Vroman, 1997; Mikkola, Rusko, Nummela, Pollari, & Hakkinen, 2007; Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003; Storen, Helgerud, Stoa, & Hoff, 2008) and highly trained (Millet, Jaouen, Borrani, & Candau, 2002; Saunders et al., 2006; Sedano, Marin, Cuadrado, & Redondo, 2013) runners through respective mechanisms that affect metabolic, biomechanical and/or neuromuscular efficiency. Performance gains following traditional heavy-resistance training are a result of predominantly neuromuscular rather than within muscle adaptations (Kraemer, Fleck, & Evans, 1996). These adaptations may include increases in strength, increased motor unit recruitment, improved mechanical efficiency and muscle coordination (Kraemer et al., 1996; Kyrolainen, Belli, & Komi, 2001; Sale, 1988). Whereas proposed explanations for the improvement following plyometric training include increased lower body muscle-tendon stiffness, degree of neural input to the muscle, enhanced muscle power development and elastic return, and improved motor unit synchronization (Paavolainen, Hakkinen, et al., 1999; Paavolainen, Nummela, Rusko, et al., 1999; Spurrs et al., 2003). The combination of resistance training and plyometric training may facilitate additional improvements in running economy via accumulation of adaptations previously observed when either type of training is performed alone. However, no studies have examined the efficacy of combining these two modes of training to elicit further improvements in running economy. Additionally, a review of the literature produced no studies examining the effects of a resistance-training intervention on running economy or performance during the competition phase of a running season, likely because coaches are often unwilling to do time trials or other performance tests that would interfere with preparations for actual competitions. In order to perform this study, I had to travel to Hope College in Holland, Michigan USA where my former cross country and track coach (who also served as the Department Chair of Kinesiology at Hope College) agreed to allow me to use his nationally competitive men's and women's cross country teams as subjects and Kinesiology Department laboratory equipment for testing. By performing the study with these teams, we were able to compare the effects of heavy resistance training versus the combination of heavy resistance- and plyometric-training on running economy in male and female runners. Additionally, performance data was collected from other cross country teams competing against Hope College throughout the NCAA cross country season in order to investigate the effects of the resistance training interventions on competition performance, using a design similar to Vandenbogaerde, Hopkins and

Pyne (2012) in which changes in performance between competitions before and after an intervention with a team of athletes can be compared with changes in performance in other team over the same time frame (Vandenbogaerde, Hopkins, & Pyne, 2012).

1.2 Overall thesis aim and questions addressed in this thesis

The overall aim of this thesis was to determine the relative efficacy of different forms of movement-specific resistance exercise to improve running economy and performance in training distance runners. An overview of the chapters included in this thesis is presented in Table 1, while the individual research questions underpinning this aim were:

- What are the lower-body determinants of running economy among male and female trained distance runners?
- What is the efficacy of augmenting running economy and performance acutely?
- What is the most effective uphill interval-training protocol to enhance running economy and performance?
- Does the addition of plyometric training to traditional heavy-resistance training enhance running economy and performance more than heavy resistance-training alone?

Table 1: Overview of the chapters included as part of the thesis.

Chapter	Title	Aim	Study Design	Significance
Chapter 2	Running economy: measurement, norms and determining factors	To consider 1) how running economy is defined and measured and 2) physiological and biomechanical factors that determine or influence running economy	Literature review	Despite being perceived as a simple concept that is simple to measure and acceptably reliable, running economy is a complex, multifactorial concept that reflects the integrated composite of a variety of metabolic, cardiorespiratory, biomechanical and neuromuscular characteristics that are unique to the individual (Anderson, 1996; Bonacci et al., 2009; Daniels, 1985; Saunders, Pyne, et al., 2004a). This multifaceted concept may be intuitively understood by scientists, practitioners and coaches, nonetheless it has yet to be defined or discussed in great detail in the literature. Therefore the purpose of Part I of this literature review was to consider the measurement, norms and multiple factors influencing running economy in trained runners. This information could provide a current comprehensive overview of the available information regarding what is and factor affecting running economy.
Chapter 3	Strategies to improve running economy	To examine various training strategies that have attempted to improve running economy, discuss the feasibility of strategies previously identified but yet to be explored in the literature, and discuss potential areas for future research.	Literature review	Running economy represents a complex interplay of physiological and biomechanical. Previous research has shown that trained runners have superior running economy to lesser-trained or untrained runners (Bransford & Howley, 1977; Daniels, Oldridge, et al., 1978; Dolgener, 1982), indicating positive adaptations occur in response to habitual training (Beneke & Hutler, 2005). This review considered a wide range of acute and chronic interventions that have been investigated with respect to improving economy by augmenting one or more components of the metabolic, cardiorespiratory, biomechanical or neuromuscular systems. This information could provide a comprehensive overview about what is presently known in regards to the various strategies to improve running economy in trained distance runners.
Chapter 4	Lower body determinants of running economy in male and female distance runners	To evaluate the lower-body determinants of running economy among well-trained male and female distance runners.	Cross-sectional descriptive design	A number of physiological, biomechanical and neuromuscular factors appear to influence running economy in trained runners. The differences in running economy that exist between males and females has been previously investigated, but with mixed findings (Bransford & Howley, 1977; Daniels, Krahenbuhl, et al., 1977; Davies & Thompson, 1979; Maughan & Leiper, 1983; Morgan et al., 1995; Morgan & Craib, 1992). Research has yet to explore which of these lower-body characteristics can explain these inter-individual differences in running economy between male and female trained distance runners. Therefore, Study 1 was designed to evaluate the lower-body determinants of running economy commonly measured in the literature. Many of the lower body characteristics measured in Study 1 represent specific or independent qualities of running economy that can be assessed and trained independently. Consequently, perhaps a greater efficiency of training can be achieved by targeting interventions that focus on those determinants in order to improve running economy.

Chapter 5	Warm-up with a weighted vest improves running performance via leg stiffness and running economy	To determine the acute effects of wearing such a vest during warm-up "strides" on neuromuscular measures, running economy and distance running performance in trained runners.	Randomized, Cross-over design	Recent research has focused on various warm-up exercises that can alter oxygen uptake (VO ₂) kinetic responses to subsequent high-intensity exercise and enhance performance (Bishop et al., 2001; Hajoglou et al., 2005; Ingham et al., 2013). However, neuromuscular characteristics have also been recognized as an important determinant of running economy and endurance performance (Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003) but no research has examined modifying these parameters acutely by different warm-up interventions to improve distance running performance. Therefore, Study 2 examined the effects of high-intensity running with an added load as part of an athlete's warm-up routine on subsequent performance. This information could provide a practical warm-up tool to enhance subsequent running performance.
Chapter 6	Effects of different uphill interval-training programs on running economy and performance	To determine the most effective uphill interval-training protocol on running economy and performance in well-trained distance runners.	Pre-post parallel-groups dose-response design	While coaches often utilize various forms of movement-specific resistance training in periodized training programs for distance runners, only anecdotal reports (Kurz et al., 2000; Midgley et al., 2007; Saunders, Pyne, et al., 2004a) and two research investigations (Ferley et al., 2012; Houston & Thomson, 1977) exist concerning the physiological responses and potential improvements in performance to such training, whereas none have examined the potential effects on running economy. In view of the uncertainty about the physiological effects of uphill training on running economy and distance running performance, Study 3 used a dose-response design (Stepto, Hawley, Dennis, & Hopkins, 1999) in order to identify the optimum training "dose" for various physiological and performance measures. The results from Study 3 could establish loading parameters for prescribing uphill training to runners based upon the desired physiological response.
Chapter 7	Effects of resistance training on running economy and cross-country performance	To compare the effects of heavy resistance training versus the combination of heavy-resistance and plyometric training on performance during the competitive phase of a men's and women's collegiate cross-country running season.	Pre-post parallel-groups design	Recent research has shown running economy to improve in runners using traditional strength training or explosive, plyometric training (Johnston et al., 1997; Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006). Heavy-resistance training and plyometric training offer distinct physiological and neuromuscular adaptations that could enhance running economy and consequently distance-running performance. To date no studies have examined the effect of combining the two modes of training on running economy or performance. To enhance the ecological validity of Study 4 I adopted a novel design (Vandenbogaerde et al., 2012) to investigate the effects of two resistance-training interventions on actual cross-country competition performance. This information could be used to better understand the effects of resistance training on competition performance and inform coaching practice.

1.3 Structure

The thesis consists of six chapters in addition to an overall introduction and rationalization (preface) (Chapter 1) and overall discussion and conclusion (Chapter 8) to the thesis. A thesis structure schematic is presented in Figure 1. All chapters are presented in the format of the journal for which they were written. The references for each chapter are collated at the end of the thesis in APA format.

The appendices (Appendix 1-5) contain subject information and ethical approval for the descriptive, acute and two experimental studies contained in this thesis.

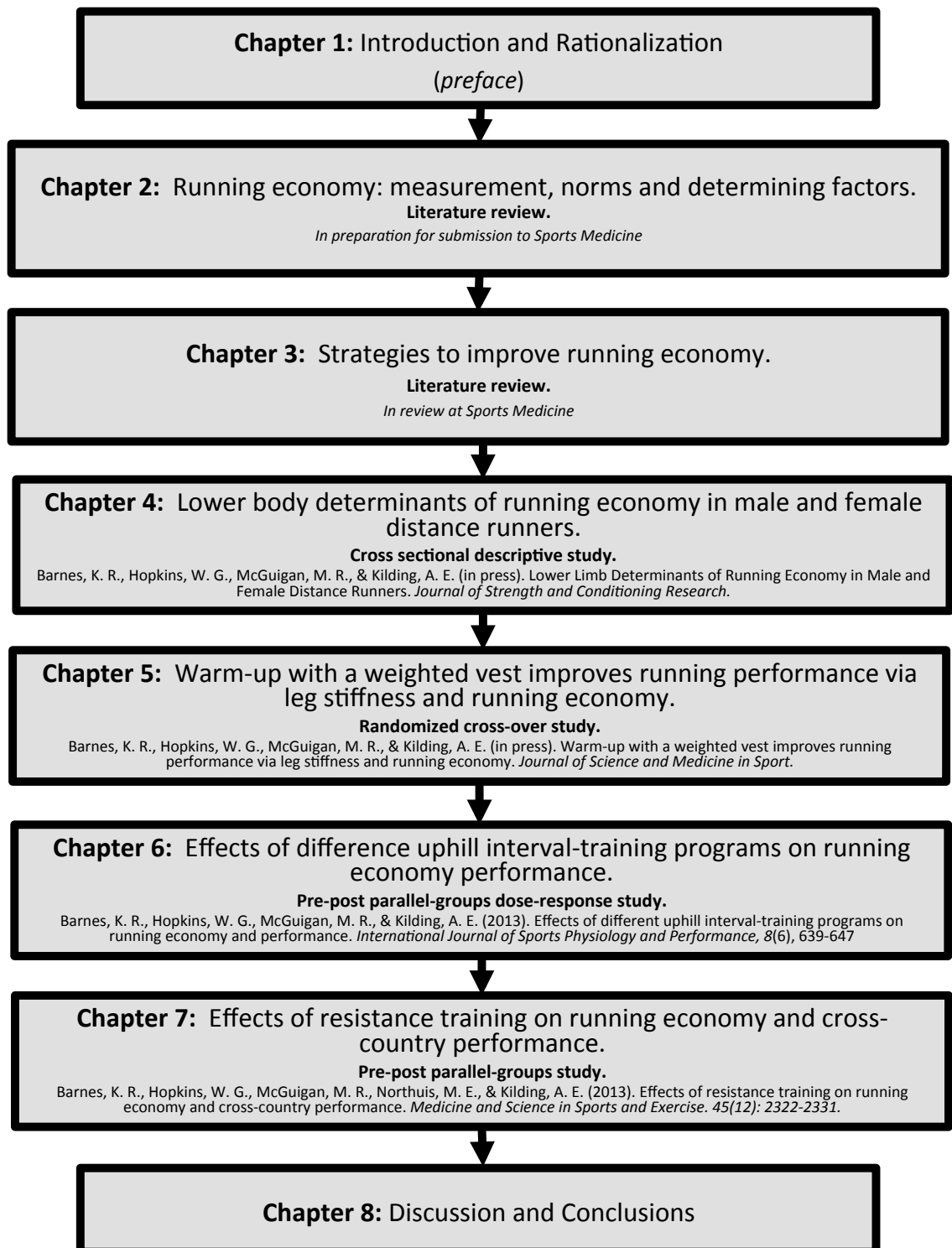


Figure 1: Overview of doctoral thesis chapter flow.

CHAPTER 2: RUNNING ECONOMY: MEASUREMENT, NORMS AND DETERMINING FACTORS

2.1 Abstract

Running economy is considered an important physiological measure for endurance athletes, especially distance runners. This review considers 1) how running economy is defined and measured and 2) physiological and biomechanical factors that determine or influence running economy. From studies conducted to date it is difficult to accurately ascertain what is good, average, and poor running economy due to variation in protocols, gas-analysis systems, and data averaging techniques, however, representative running economy values for different caliber of male and female runners can be identified from existing literature with mostly clear delineations in oxygen uptake across a range of speeds in moderately and highly trained and elite runners. Despite being simple to measure and acceptably reliable, it is evident that running economy is a complex, multifactorial concept that reflects the integrated composite of a variety of metabolic, cardiorespiratory, biomechanical and neuromuscular characteristics that are unique to the individual. Metabolic and cardiorespiratory efficiency refers to processes that result in better use of oxygen (increased energy production) relative to a given work output. Fluctuations in cardiorespiratory function, thermoregulation, and substrate metabolism have been associated with changes in running economy. Likewise, anthropometric dimensions, select gait patterns, and flexibility have been shown to affect biomechanical efficiency and relate to better running economy. Neuromuscular characteristics, including lower body stiffness, force production, neural signaling, and motor programming are also important aspects of running economy.

2.2 Introduction to Measurement, Norms and Determining Factors

The steady-state oxygen consumption (VO_2) at a given running velocity, which is often referred to as running economy (Conley & Krahenbuhl, 1980; Daniels, 1985; Saunders, Pyne, et al., 2004a), reflects the energy demand of running at a constant submaximal speed. Runners with good economy use less oxygen than runners with poor economy at the same steady-state speed (Figure 2) (Thomas, Fernhall, & Granat, 1999). It has been reported that running economy can vary by as much as 30% among trained runners with similar $\text{VO}_{2\text{max}}$ (Daniels, 1985). Previous studies indicate that differences in an athlete's running economy are likely related to a number of independent physiological, biomechanical, anthropometric, environmental and training related factors (Figure 3) (Anderson, 1996; Saunders, Pyne, et al., 2004a). Running economy has also been shown to be a useful predictor of endurance running performance, especially in athletes who are homogenous with respect to $\text{VO}_{2\text{max}}$ (Figure 2) (Conley & Krahenbuhl, 1980; Costill et al., 1973; Morgan, Baldini, et al., 1989). Therefore it would appear that running economy is an important measure to quantify and attempt to enhance.

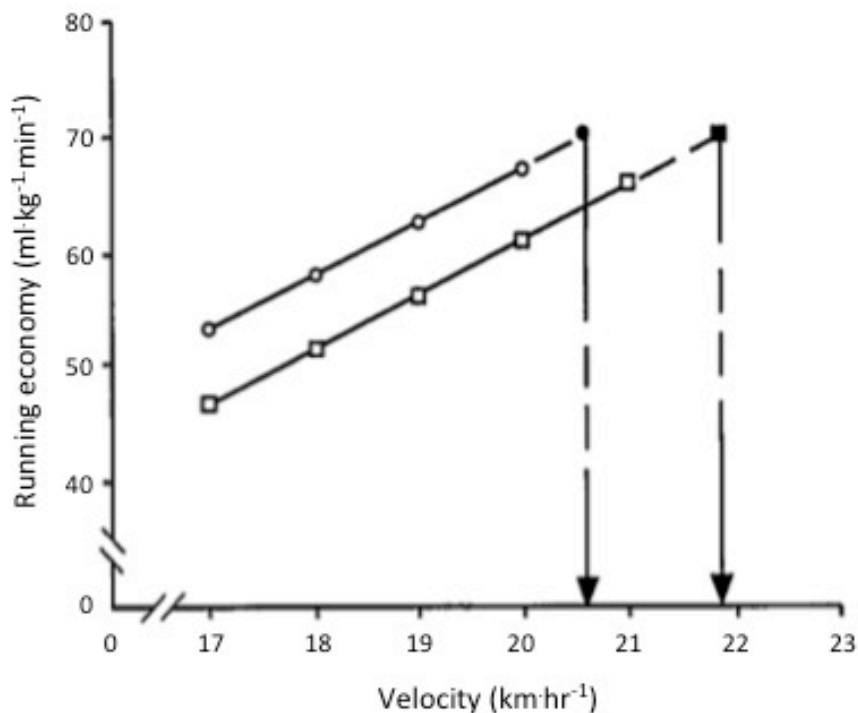


Figure 2: Running economy profiles of two runners of equal $\text{VO}_{2\text{max}}$. Adapted from Daniels and Daniels (Daniels & Daniels, 1992).

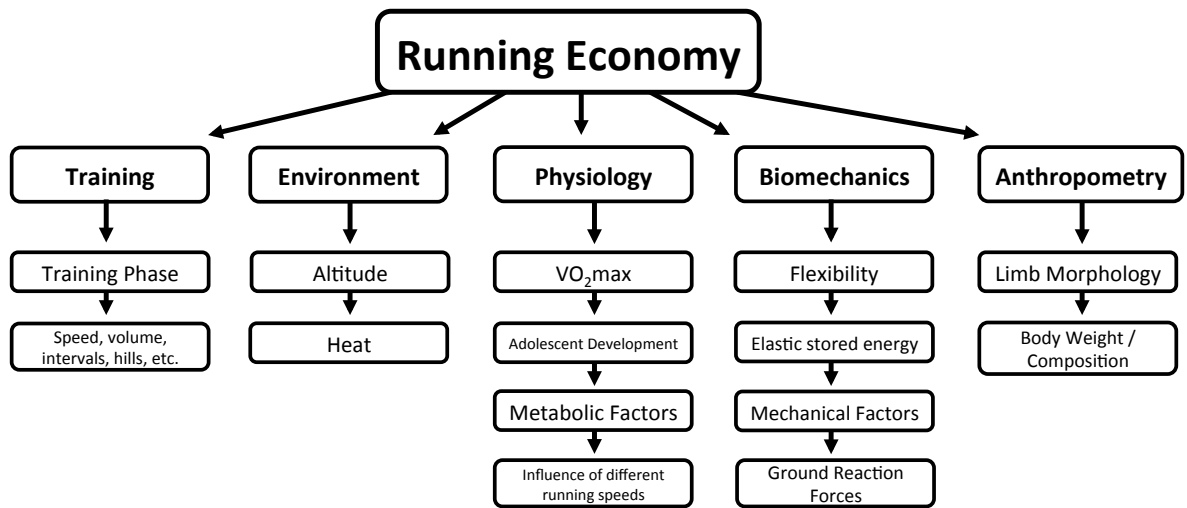


Figure 3: Factors affecting running economy (adapted from Saunders et al. (2006)).

While the measurement of running economy is often perceived as a simple concept, it is actually a multifactorial measure which reflects the combined functioning of various the metabolic, cardiopulmonary, biomechanical and neuromuscular systems (Anderson, 1996; Bonacci et al., 2009; Daniels, 1985; Saunders, Pyne, et al., 2004a). Metabolic efficiency refers to the utilization of available energy to facilitate optimal performance (Daniels, 1985; Saunders, Pyne, et al., 2004a), whereas cardiopulmonary efficiency refers to a reduced work output for the processes related to oxygen transport and utilization. Biomechanical efficiency refers to the mechanical cost of running including factors such as energy storage and how wasteful the movement pattern is. Lastly, neuromuscular efficiency refers to the interaction between the neural and musculoskeletal systems and its ability to effectively translate cardiorespiratory capacity into movement and therefore into performance (Bonacci et al., 2009). The multifaceted concept of running economy, with multiple types of efficiency (that is, accounting for the work done and energy lost) may be intuitively understood by scientists, practitioners and coaches, nonetheless it has yet to be defined or discussed in great detail in the literature. The purpose of this review is to consider the multiple factors influencing running economy in trained runners and secondly. Specifically, in Part I, we will 1) examine and review how running economy is defined and measured and 2) consider the metabolic, cardiorespiratory, biomechanical, and neuromuscular components that determine running economy. In Part II, we will examine various training strategies to improve running economy, and discuss potentials areas for future research.

2.3 Defining and Measuring Running Economy

It has been suggested that work economy for a given task has emerged as a measurement which is both conceptually clear and practically useful for the evaluation of endurance activities and has become almost universally accepted as the physiological criterion for 'efficient' performance (Cavanagh & Kram, 1985a). Despite this, there is a discrepancy over the term running economy and its definition. Conley and Krahenuhl (1980) define economy as submaximal oxygen consumption ($VO_{2\text{submax}}$) (Conley & Krahenbuhl, 1980). Williams (1985) refers to $VO_{2\text{submax}}$ for a given task as the "physiological efficiency" and Goldspink (1977) claims that economy usually refers to muscle efficiency (Goldspink, 1977; Williams, 1985). Efficiency refers to the ratio of work done to energy expended, and thus the terms "efficient" and "efficiency" should not be used to relate the energy demands of running to velocity of running because running velocity represent only part of the work being performed by the body while it is transported from one point to another (Daniels, 1985). Other terms such as "cost," "oxygen cost," "energy cost," and "requirement" have all found their way into the literature as ways of describing the relationship between oxygen consumption (VO_2) and running velocity (Daniels, 1985). The energy cost of running reflects the sum of both aerobic and anaerobic metabolism, and the aerobic demand, measured by the VO_2 in $L \cdot \text{min}^{-1}$ at a given speed does not necessarily account for the energy cost of running, which is measured in joules, kilojoules, calories or kilocalories of work done (Daniels, 1985; Fletcher, Esau, & Macintosh, 2009; Saunders, Pyne, et al., 2004a).

Running economy is represented by the energy demand for a given velocity of submaximal running and expressed as the submaximal VO_2 at a given running velocity (Conley & Krahenbuhl, 1980; Daniels, 1985; Saunders, Pyne, et al., 2004a). This value reflects gross or total economy; a measurement that represents the metabolic, cardiorespiratory, biomechanical and neuromuscular components of running without consideration for what portion of that VO_2 is a function of good or bad mechanics as opposed to being related to differences in metabolism or force production which may exist in different athletes or under different conditions (Anderson, 1996; Bonacci et al., 2009; Daniels, 1985). Additionally, it often gets overlooked that it is possible to become more efficient in one area yet have total running economy be negatively affected because of a larger decrease in another aspect of efficiency. Accordingly, the measure of running economy may be flawed as it is determined by multiple variables that may or may not be based on oxygen consumption alone, nevertheless, having an understanding of the underlying idea of running economy provides insight into the complexity of this measurement. Still being able to describe the VO_2 related to a particular velocity of running provides a useful way of comparing individuals, or any

individual with him or herself under various conditions and this VO_2 gives a measure of running economy. Despite its apparent shortcomings, such will be the indicator of running economy used throughout this thesis.

The standard approach to quantifying running economy involves measuring VO_2 while running on a treadmill at various constant speeds for a duration long enough to achieve physiological steady-state. Typically, durations of 3 to 15 min have been used in studies if the speed is below the ventilatory/lactate threshold (Morgan, Martin, & Krahenbuhl, 1989), since above this intensity, a slow component of VO_2 is evident (Jones, Koppo, & Burnley, 2003). Often, the steady-state condition is verified by considering other physiological parameters such as verifying that blood lactate concentration is similar to baseline levels (MacDougall, 1977) and the respiratory exchange ratio (RER) is < 1 (Conley & Krahenbuhl, 1980).

2.3.1 Normative Data

Although the aerobic demands of submaximal running have been investigated for many years, $\text{VO}_{2\text{max}}$ has generally been the factor receiving most attention relative to identifying talented endurance athletes. However, among a homogeneous group of runners, $\text{VO}_{2\text{max}}$ is poorly correlated, and running economy is highly correlated with distance running performance (Daniels & Daniels, 1992). Unfortunately no study to date has compiled reference data from the available literature to establish normative ranges for elite, highly trained, moderately trained and recreational runners. Comparisons between individuals running economy are traditionally made by interpolating (or extrapolating) the VO_2 to a common running velocity and expressing running economy relative to body mass per minute ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) or by the total volume of oxygen needed to run one kilometer relative to body mass ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) (Foster & Lucia, 2007). The most commonly used reference velocity is $16\text{ km}\cdot\text{hr}^{-1}$ ($268\text{ m}\cdot\text{min}^{-1} = 4.47\text{ m}\cdot\text{s}^{-1}$), which represents 6 minutes per mile, or 3 min 44 sec per km, however, velocities from 12 to $21\text{ km}\cdot\text{hr}^{-1}$ appear in the literature (Brisswalter & Legros, 1994a; Conley & Krahenbuhl, 1980; Costill et al., 1973; Daniels & Daniels, 1992; Daniels, Krahenbuhl, et al., 1977; Daniels, Scardina, Hayes, & Foley, 1986; Joyner, 1991; Lucia et al., 2006; Lucia, Olivan, Bravo, Gonzalez-Freire, & Foster, 2008; Morgan, Craib, et al., 1994; Morgan & Daniels, 1994; Pollock, 1977; Saltin et al., 1995; Saunders, Pyne, et al., 2004a; Saunders, Pyne, Telford, & Hawley, 2004b; Williams, Krahenbuhl, & Morgan, 1991). Daniels and Daniels (1992) explain that by plotting VO_2 data against running velocity, 'economy curves' can be generated for athletes and the resulting regression equations can be used to generate VO_2 values for the exact common speeds used for comparison (Figure 2) (Daniels & Daniels, 1992). Not all research

available provides these equations; therefore in the future more researchers should provide the regression equations for their sample when measuring running economy across a range of running speeds.

From the studies to date it is difficult to accurately ascertain what is good, average, and poor running economy due to variation in protocols, gas-analysis equipment, data averaging techniques and differences in maximal aerobic capacity. However, acknowledging these potential limitations, representative VO_2 values for different caliber of runners from the existing literature are presented in Table 2. The lowest reported value for VO_2 at $16 \text{ km}\cdot\text{hr}^{-1}$ is $39.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ in an individual East African runner, capable of running 1500m in 3:35 with a $\text{VO}_{2\text{max}}$ of only $63 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Foster & Lucia, 2007). However, the current Men's Half Marathon World Record holder's (Tadesse Zerisenay, 58 min 23 s; $\text{VO}_{2\text{max}} = 83.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) running economy was measured at $150 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $19 \text{ km}\cdot\text{hr}^{-1}$ ($317 \text{ m}\cdot\text{min}^{-1}$) which is equivalent to $40.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $16 \text{ km}\cdot\text{hr}^{-1}$ or 48.2% relative intensity of effort compared to 61.9% of the aforementioned athletes $\text{VO}_{2\text{max}}$ (Lucia et al., 2008). The concept of relative intensity is an important one because trained runners all perform at near equal percentages of their respective $\text{VO}_{2\text{max}}$ depending on the distance of the event in question (Figure 4) (Daniels & Daniels, 1992; Daniels & Gilbert, 1979). Other examples of exceptional running economy include Paula Radcliffe (Women's Marathon World Record holder, 2 hr 15 min 25 s; $\text{VO}_{2\text{max}} = 75.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) $44.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $16 \text{ km}\cdot\text{hr}^{-1}$ (Jones, 2006); Frank Shorter (Men's Olympic Marathon Gold [1976] and Silver [1980] medalist; $\text{VO}_{2\text{max}} = 71.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) $57.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $19.3 \text{ km}\cdot\text{hr}^{-1}$ (Pollock, 1977); and Jim Ryun (former Men's 880 yd, 1 min 44.9 s; 1500 m, 3 min 33.1 s; 1 mile, 3 min 51.1 s World Record holder; $\text{VO}_{2\text{max}} = 78.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) $48.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $16 \text{ km}\cdot\text{hr}^{-1}$ (Daniels, 1974b).

Table 2: Normative running economy data for male and female runners of varying ability levels.

Runner classification	Speed (km·hr ⁻¹)	Male mean (range)		Female mean (range)	
		Running economy (ml·kg ⁻¹ ·min ⁻¹)	VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	Running economy (ml·kg ⁻¹ ·min ⁻¹)	VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)
Recreational ^a	10	36.7 (35.4-38.8)		37.7 (32.8-42.6)	
	12	42.2 (40.4-45.3)	54.2 (51.0-57.8)	43.2 (38.5-48.1)	49.7 (45.2-54.1)
	14	47.4 (46.0-49.5)		47.3 (40.1-51.9)	
Moderately trained ^b	12	40.7 (37.4-48.1)		41.9 (28.9-41.7)	
	14	46.8 (42.0-55.5)	62.2 (56.6-69.1)	47.9 (41.3-53.5)	55.8 (50.5-59.4)
	16	51.4 (51.6-62.3)		52.9 (45.7-61.0)	
Highly trained ^c	12	n/a		41.3 (33.3-50.2)	
	14	45.0 (32.4-56.5)		48.3 (39.0-56.7)	
	16	50.6 (40.5-66.8)	70.8 (65.3-80.2)	54.5 (46.2-61.9)	61.7 (56.2-72.3)
	18	58.1 (48.0-72.0)		58.6 (54.4-67.1))	
	20	66.5 (65.7-71.6)		n/a	
Elite ^d	14	39.9 (36.1-44.5)		41.9 (38.7-46.9)	
	16	47.9 (43.2-53.4)	75.4 (68.2-84.1)	48.9 (45.1-55.8)	66.2 (61.1-74.2)
	18	55.9 (50.5-62.3)		56.1 (51.8-63.8)	
	20	63.91 (57.5-71.2)		n/a	

n/a = not applicable.

^a(Albracht & Arampatzis, 2013; Cheng et al., 2012; Ferrauti, Bergermann, & Fernandez-Fernandez, 2010; Foster & Lucia, 2007; Franch et al., 1998; Taipale et al., 2009; Taipale, Mikkola, Vesterinen, et al., 2013)

^b(Berryman et al., 2010; Denadai et al., 2006; Guglielmo et al., 2009; Johnston et al., 1997; Mikkola et al., 2011; Spurrs et al., 2003; Storen et al., 2008)

^c(Conley & Krahenbuhl, 1980; Daniels, Krahenbuhl, et al., 1977; Daniels, Scardina, & Foley, 1984; Daniels et al., 1986; Morgan, Craib, et al., 1994; Saunders & Green, 2013; Saunders, Pyne, et al., 2004b)

^d(Daniels, 1974a; Daniels & Daniels, 1992; Daniels et al., 1986; Pollock, 1977; Saunders, Pyne, et al., 2004b; Saunders et al., 2006)

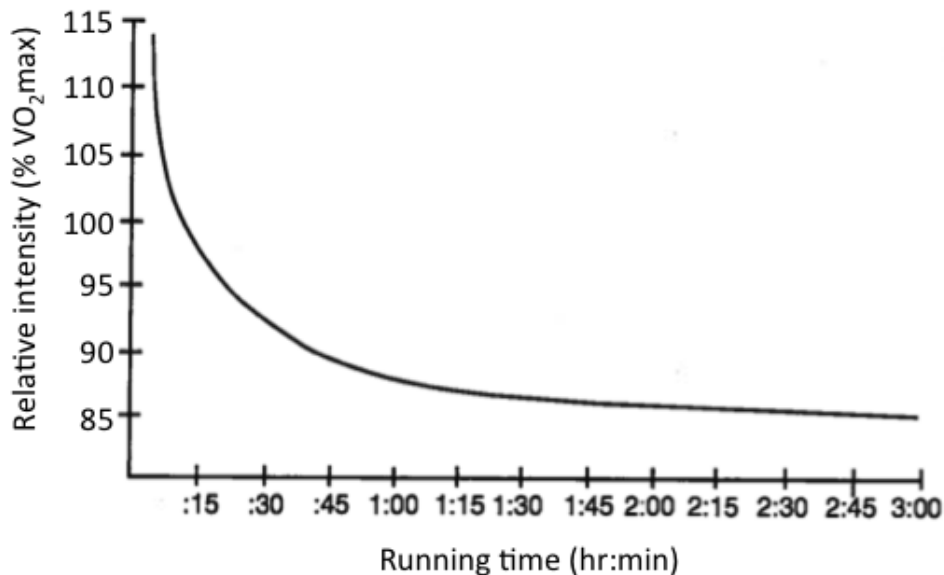


Figure 4: Relationship between race duration and relative intensity. Adapted from Daniels et al. (1978) (Daniels, Fitts, & Sheehan, 1978).

2.3.2 Treadmill and Overground Running

Due to the difficulty of obtaining metabolic data during overground running in the field (i.e. during training and competitions), measurements of running economy have typically been made in the laboratory on motorized treadmills during which pulmonary gas-exchange is determined during bouts of constant-speed running and analyzed using various forms of manual (i.e. Douglas bag method) (Truijens et al., 2008) or automated (i.e. breath-by-breath gas-analysis systems) (Barnes, Hopkins, McGuigan, & Kilding, 2013b; Barnes, Hopkins, McGuigan, Northuis, et al., 2013). However, since air and wind resistance are not factors during laboratory testing, transferring treadmill data to overground running requires caution (Daniels, 1985; Morgan, Martin, et al., 1989; Saunders, Pyne, et al., 2004a). Specifically, differences between overground and treadmill running are likely to be found since as speed increases the effects of air and wind resistance become more pronounced (more on air and wind resistance in Kinetics / Ground Reaction Forces section below) (Daniels, 1985; Daniels, Foster, et al., 1977). Furthermore, the technique of running on a treadmill is different to running over ground where the hamstrings are used to a greater extent to produce propulsive horizontal and vertical forces (Jones & Doust, 1996). For these reasons, data collected during laboratory treadmill testing sessions are typically under-estimations of the true energy demands during over ground running, although a slight incline on the treadmill gradient (~1%) can be used to increase the energy demand in compensation for the lack of air resistance experienced during overground running (Jones & Doust, 1996). In recent years, however, lightweight, accurate, portable telemetric metabolic measuring systems have been designed that enable researchers and practitioners to

obtain measurements during running outside of a laboratory environment. Although, Saunders et al. (2004) note that careful attention must be made to ensure post- or repeated-measure results are not influenced by changes in environmental conditions (Saunders, Pyne, et al., 2004a).

2.3.3 Reliability of Running Economy

In order to evaluate the effectiveness of running training throughout the season or the effect of specific interventions aimed at improving running economy, the intraindividual variation (typical error) of running economy should be considered. Factors such as treadmill running experience (Morgan, Martin, Krahenbuhl, & Baldini, 1991), training level (Pereira & Freedson, 1997), footwear (Morgan, Martin, Baldini, & Krahenbuhl, 1990; Morgan et al., 1991; Pereira & Freedson, 1997; Pereira, Freedson, & Maliszewski, 1994; Saunders, Pyne, et al., 2004b), time of day of testing (Morgan et al., 1990; Morgan et al., 1991; Pereira & Freedson, 1997; Pereira et al., 1994; Saunders, Pyne, et al., 2004b), prior training activity (Morgan et al., 1991; Pereira et al., 1994), nutritional status (Pereira & Freedson, 1997; Pereira et al., 1994), testing equipment (Saunders, Pyne, et al., 2004b) and laboratory environment (Saunders, Pyne, et al., 2004b) may affect the test-retest reliability of running economy measures. Well-controlled studies using moderately trained to elite caliber subjects report intraindividual variation in running economy between 1.3% and 5% at speeds between 12 and 18 km·hr⁻¹ (Barnes, Hopkins, McGuigan, Northuis, et al., 2013; Brisswalter & Legros, 1994a; Morgan, Craib, et al., 1994; Morgan et al., 1990; Morgan et al., 1991; Pereira & Freedson, 1997; Pereira et al., 1994; Saunders, Pyne, et al., 2004b; Williams et al., 1991) indicating that within-subject results are relatively stable. While no patterns emerge between the training status or gender of the athlete and reliability of running economy, it does appear that the typical error is less at running velocities at which the athletes typically train (Morgan et al., 1991; Pereira & Freedson, 1997; Saunders, Pyne, et al., 2004b). While durations of up to 15 min have been used in the assessment of running economy (Pereira & Freedson, 1997), multiple ~4 min stages at progressively faster running speeds (e.g. 12, 14, 16, 18 km·hr⁻¹) have been used in moderate to highly trained runners familiar with treadmill running because steady-state VO₂ can be reached within 2-3 min at each running speed (Saunders, Pyne, et al., 2004b).

Additionally, Hopkins (2000) has proposed the concept of the smallest worthwhile change (SWC) to determine the practical significance of interventions (Hopkins, 2000). The SWC identifies the magnitude of change required to elicit a meaningful or significant improvement in running economy. The SWC, calculated as a

proportion of the effect size, represents the magnitude of improvement in a variable as a function of the between-athlete standard deviation of the particular cohort (Hopkins, Marshall, Batterham, & Hanin, 2009; Hopkins, Schabert, & Hawley, 2001). Saunders et al. (2004) estimated a SWC of 2.6%, 2.4%, and 2.2% for running economy at 14, 16, and 18 km·h⁻¹ respectively in 70 highly trained distance runners (Saunders, Pyne, et al., 2004b). Therefore, a distance runner must improve their running economy by ~2.2-2.6% before a coach or practitioner can be reasonably confident that a real change (improvement) has occurred.

2.4 Metabolic and Cardiorespiratory Efficiency

In the context of improving running economy, metabolic and cardiorespiratory efficiency refers to processes that result in better use of oxygen (increased energy production) relative to a given work output. Fluctuations in cardiorespiratory measures [heart rate (HR), minute ventilation (V_E)], thermoregulation [core temperature (C_{Temp})], and substrate metabolism [muscle contractile efficiency, mitochondrial efficiency] have been associated with changes in running economy (Bailey & Pate, 1991; Jones, 2013; Morgan & Craib, 1992; Pate, Macera, Bailey, Bartoli, & Powell, 1992; Saunders, Pyne, et al., 2004a; Svedenhag, 2000).

2.4.1 Cardiorespiratory Measures

Bailey and Pate (1991) and Pate et al. (1989) have suggested that changes in cardiorespiratory measures (HR and V_E) are partly responsible for changes in running economy during submaximal and maximal exercise (Bailey & Pate, 1991; Pate, 1989). Thomas et al. (1995) found a correlation of $r = 0.79$ ($p < 0.05$) between changes in V_E and changes in running economy during a 5-km race in trained female runners (Thomas, Fernhall, & Blanpied, 1995). The decreased running economy was postulated to be caused by the increased O_2 demand of breathing (Hagberg, Mullin, & Nagle, 1978). Franch et al. (1998) also reported a correlation ($r = 0.77$; $p < 0.0001$) between improvements in running economy and reductions in pulmonary ventilation which may account for 25-70% of the decrease in aerobic demand after an intense run training program in recreational runners (Franch et al., 1998). Another study attempted to determine the impact of a simulated 5-km race on running economy, V_E , HR, and C_{Temp} (Thomas et al., 1999). Consistent with other findings (Bailey & Pate, 1991; Thomas et al., 1995), running economy decreased significantly and V_E , HR, and C_{Temp} all increased significantly from the beginning to the end of the 5-km run. Similar to previous studies (Franch et al., 1998; Thomas et al., 1995), the increase in V_E was the only measure related to the increased running economy ($r = 0.64$; $p < 0.05$). The fact that the two variables were correlated in several studies does in itself imply cause and

effect; however, quantitative estimates of the reduced cost of breathing with the training-induced decrement in V_E suggest that ventilatory adaptation may indeed play a role in improving running economy (Franch et al., 1998).

Interindividual variation in running economy has been linked to differences in HR and V_E . In a report by Pate et al. (1989) involving 167 habitual runners, both HR and V_E were significantly and positively correlated with VO_2 (Pate, 1989), indicating that better running economy was associated with lower HR and V_E . Myocardial VO_2 also constitutes a significant fraction (1-2%) of whole body VO_2 during exercise (Kitamura, Jorgensen, Gobel, Taylor, & Wang, 1972). Reductions in myocardial VO_2 would result in improved running economy from a more efficient combination of HR and stroke volume (i.e. a reduction in HR and increase in stroke volume) (Pate, 1989). However, according to Bailey and Pate (Bailey & Pate, 1991) it is unlikely changes in HR make a significant contribution to changes in running economy. A 20-bpm change in HR only increased VO_2 by $8 \text{ ml}\cdot\text{min}^{-1}$, which increased running economy from 41.8 to $41.9 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Voluntary hyperpnoea at rest, which increased V_E from 70 to $100 \text{ ml}\cdot\text{min}^{-1}$, has been found to increase VO_2 by $122 \text{ ml}\cdot\text{min}^{-1}$ (Coast & Krause, 1993). If training is able to decrease the work of breathing at a specific running velocity, this could contribute to an improved running economy (Bailey & Pate, 1991). Using recent cost estimates of exercise V_E , the cost of V_E increased O_2 consumption by 31 - 50 ml (0.4 - $0.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) in men and 19 - 31 ml (0.3 - $0.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) in women. This explains 12 - 19% of the increase in VO_2 in men and 16 - 26% for the women (Aaron, Seow, Johnson, & Dempsey, 1992; Poole, 1994). Other estimates have found the work of ventilation to constitute up to 6 - 7% of the total oxygen cost of exercise (Milic-Emili, Petit, & Deroanne, 1962). Thus variables other than V_E are also responsible for the changes in running economy.

2.4.2 Body Temperature

There is conflicting evidence regarding the relationship between C_{Temp} and running economy (Bailey & Pate, 1991; Morgan et al., 1990). In some studies, a higher C_{Temp} has resulted in an increase in VO_2 at a given speed under hyperthermic conditions (MacDougall, Reddan, Layton, & Dempsey, 1974; Saltin, 1964), likely due to increases in metabolic demand from augmented circulation, sweating, V_E , and a decrease in efficiency of oxidative phosphorylation (Brooks, Hittelman, Faulkner, & Beyer, 1971a, 1971b; MacDougall et al., 1974). In this regard, Grimby (1962) found that a 1.3° C increase in C_{Temp} increased VO_2 by 5.5% (Grimby, 1962) and Thomas (1999) found a slightly greater change in VO_2 (6.2%) after a 1.0° C increase in C_{Temp} (Thomas et al., 1999). In contrast, results from other studies (Maron, Horvath,

Wilkerson, & Gliner, 1976; Rowell, Brengelmann, Murray, Kraning, & Kusumi, 1969) indicate no change or a reduction in VO_2 occurred during hyperthermic exercise, suggesting a higher C_{Temp} enhanced mechanical efficiency of muscle to a degree equal to or greater than the increase caused by changes in circulation, sweating, and V_E . Additionally, Bailey and Pate (1991) suggest that training-induced adaptations to repeated bouts of exercise in the heat (Bailey & Pate, 1991), such as increased plasma volume, may attenuate the thermoregulatory response and reduce attendant energy requirements (See Training in the Heat in Part II), potentially resulting in improved running economy.

2.4.3 Muscle Fiber Type

It is now accepted that a range of muscle fiber types exist in humans (Bosco et al., 1987; Williams & Cavanagh, 1987) and that each exhibit their own metabolic characteristics (Morgan & Craib, 1992). Indeed, the structure and composition of muscle fibers seems to influence running economy (Kaneko, 1990; Kyrolainen et al., 2003; Morgan & Craib, 1992). Type IIA fibers are more oxidative than type IIX fibers and have functional characteristics more similar to type I fibers (Johnston et al., 1997). Type-II specific myosin ATPase isoforms require 1.6- to 2.1-fold more ATP per unit force production than type I and therefore require a proportionately higher oxidative phosphorylation (Rowlands, Graham, Fink, Wadsworth, & Hughes, 2013). Therefore an increase in type IIA fibers should increase the oxidative capacity of muscle and should contribute to improved running economy. Although no research has examined the genetic link between muscle fiber type and running economy, athletes may be predisposed to better or worse economy based on their composition of type I and type II muscle fibers (Tucker, Santos-Concejero, & Collins, 2013). Several studies have found a correlation between the percentages of type I muscle fibers and running economy (Bosco et al., 1987; Kaneko, 1990; Williams & Cavanagh, 1987), indicating that metabolic activity or actual speed of contraction of the muscle fibers may influence running economy. Although, Williams and Cavanagh (1987) observed no difference in muscle fiber composition among 31 trained male runners who exhibited good, medium and poor running economy (Williams & Cavanagh, 1987), Bosco et al. (1987) reported a significant positive relationship ($r = 0.60$; $p < 0.01$) between percent type II fibers and running economy in 17 athletes (Bosco et al., 1987). In further support, Kyrolainen et al. (2003) found a difference in running economy at six different running speeds among a group of homogeneous middle-distance runners, which was partly explained by differences in muscle fiber distribution, myosin heavy chain isoform composition, and titin isoforms (Kyrolainen et al., 2003). Specifically, at a speed of $7 \text{ m}\cdot\text{s}^{-1}$, VO_2 was inversely correlated with the amount of myosin heavy chain II isoforms and with

percent Type II fibers, which is in contrast to the findings of Bosco et al. (1987) (Bosco et al., 1987). Additionally, the percentage of type II fibers as fast myosin heavy chain isoforms correlated positively with the maximal force and with the rate of force production (Kyrolainen et al., 2003). Titin is a large elastic protein acting as anchor between the Z-lines and myosin within the sarcomere, which may play a significant role in running economy (Kyrolainen et al., 2003). Whereas myosin is directly involved in the force production processes of muscle contraction, titin is thought to have effects on the elastic characteristics of the muscle fibers (Wang, McCarter, Wright, Beverly, & Ramirez-Mitchell, 1993). Because force production is an important determinant of muscle-tendon performance (stiffness and storage and return of elastic energy) during running, myosin heavy chain isoforms and titan may affect neuromuscular efficiency and therefore running economy.

In summary, a number of metabolic and cardiorespiratory measures appear to influence running economy. Heart rate and V_E make a substantial contribution to overall VO_2 and are associated with interindividual differences and improvements in running economy. Muscle structure also seems to play an important role in explaining differences between athletes and perhaps changes in running economy following training, which can be partly explained by muscle fiber distribution, myosin heavy chain composition, and titin isoforms. The effects of C_{Temp} on running economy are inconsistent, however; training-induced adaptations as a result of prolonged exposure to the heat may provide a means of improving running economy.

2.5 Biomechanical Efficiency

Running involves the conversion of muscular forces translocated through complex movement patters that utilize all the major muscles and joints in the body (Anderson, 1996). Current evidence suggests that a variety of biomechanical characteristics are likely to contribute to running economy; these include a variety of anthropometric dimensions (Bourdin, Pastene, Germain, & Lacour, 1993; Cavanagh & Kram, 1985b, 1989; Pate et al., 1992; Scholz, Bobbert, van Soest, Clark, & van Heerden, 2008; Taylor, Heglund, & Maloiy, 1982; Williams & Cavanagh, 1986; Williams & Cavanagh, 1987), select gait patterns (Cavagna, Heglund, & Willems, 2005; Cavanagh & Williams, 1982; Di Michele & Merni, 2013; Morgan, Martin, et al., 1994; Morgan & Martin, 1986; Nilsson & Thorstensson, 1987; Svedenhag & Sjodin, 1984; Tartaruga et al., 2012), and kinematic and kinetic factors (Anderson & Tseh, 1994; Cavanagh, Pollock, & Landa, 1977; Chang & Kram, 1999; Farley & McMahon, 1992; Heise & Martin, 2001; Kram & Taylor, 1990; Tartaruga et al., 2012; Williams & Cavanagh, 1986; Williams & Cavanagh, 1987; Williams, Cavanagh, & Ziff, 1987) that

have been shown to affect biomechanical efficiency and relate to better running economy.

2.5.1 Anthropometric Characteristics

2.5.1.1 Body Mass and Mass Distribution

A variety of anthropometric characteristics such as height, body mass, physique, and segmental mass distribution may help explain interindividual and group differences as well as potential influences on running economy. It is well-known that the oxygen cost of running does not increase proportional to body mass (Taylor, 1994; Taylor et al., 1982), and the VO_2 per kilogram of body mass is higher in children than adults (Daniels, 1985; Daniels & Oldridge, 1971; Daniels, Oldridge, et al., 1978; Krahenbuhl & Pangrazi, 1983; Krahenbuhl, Pangrazi, & Chomokos, 1979; MacDougall, Roche, Bar-Or, & Moroz, 1983; Morgan, Martin, et al., 1989; Rowland et al., 1997; Rowland, Auchinachie, Keenan, & Green, 1987, 1988; Silverman & Anderson, 1972; Thorstensson, 1986; Unnithan, Timmons, Brogan, Paton, & Rowland, 1996). Indeed, in running events ranging from 800-m to the marathon, it's not uncommon to see individuals range by as much as 25 kg and/or 30 cm in the same race, even at the elite level. For this reason, it has been suggested that scaling body mass to the 0.67 or 0.75 power (e.g. $\text{ml}\cdot\text{kg}^{-0.67}\cdot\text{min}^{-1}$ or $\text{ml}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$) is more appropriate when comparing groups or individuals (Åstrand, 2003; Bergh, Sjodin, Forsberg, & Svedenhag, 1991; Daniels & Daniels, 1992; Heil, 1997; Rogers, Olson, & Wilmore, 1995; Svedenhag & Sjodin, 1994; Welsman, Armstrong, Nevill, Winter, & Kirby, 1996). For example, several studies (Davies & Thompson, 1979; Skinner, Hutsler, Bergsteinova, & Buskirk, 1973) have shown lightweight men to be no more or less economical than their heavier counterparts. Other research has demonstrated that when body mass is artificially increased by adding weight to the trunk, the VO_2 per kilogram of body mass has been found to decrease in children (Cooke, McDonagh, Nevill, & Davies, 1991; Davies, 1980b; Thorstensson, 1986) and adults (Abe et al., 2011; Cooke et al., 1991; Thorstensson, 1986) during running. Consequently, several authors have suggested that the lower submaximal VO_2 in adults compared with children is a function of differences in body mass and not merely growth and maturation (Bergh et al., 1991; Sjodin & Svedenhag, 1992). In support, several studies (Bourdin et al., 1993; Pate et al., 1992; Williams & Cavanagh, 1986; Williams & Cavanagh, 1987) have shown small to moderate inverse relationship between body mass and running economy.

The relationship between body mass and running economy has been proposed to be a result of individual differences in mass distribution within the body, particularly

in the limb segments (Cavanagh & Kram, 1985b). For example, subtle differences in physique, particularly a low body mass index (BMI) and long slender legs where the majority of mass is distributed higher on the thigh, have been suggested to be the primary reason for the extraordinary running economy of African runners (Foster & Lucia, 2007; Larsen, 2003; Lucia et al., 2006; Wilber & Pitsiladis, 2012). Although it is difficult to obtain a direct measure of the relationship between segmental mass distribution and running economy, indirect support comes from experimental studies in which mass has been added to the lower limb segments of runners (Catlin, 1979; Cureton et al., 1978; Jones, Toner, Daniels, & Knapik, 1984; Keren, Epstein, Magazanik, & Sohar, 1981; Martin, 1985; Myers & Steudel, 1985; Soule & Goldman, 1969). In general, the results from these studies indicate that the aerobic demand of carrying an extra load becomes more significant when the mass is located more distally. Myers (1985) found that the aerobic demand of carrying an extra kilogram on the trunk is increased by 1% whereas when an equal mass is carried in the shoes, aerobic demand is increased by 10% (Myers & Steudel, 1985). Other studies have found an increased VO_2 of 4.5% (Jones, Knapik, Daniels, & Toner, 1986) and 14% (Martin, 1985) per kilogram carried on the feet and 7% increase when carried on the thigh (Martin, 1985). Given the distal location of the feet, foot size or foot size relative to body size would also suggest it influences running economy (Anderson, 1996). If one considers that a typical standard shoe weighs about 350 g, about 200 g more than most minimal shoes, and that the aerobic demand for every 100 g added to the trunk increases by about 0.1% and added to the foot increases by 1.0% (Frederick, 1984; Myers & Steudel, 1985), then the results from Perl et al. (2012) suggest the net savings to minimal-shoe running is between 4.4% and 6.8% (Perl, Daoud, & Lieberman, 2012). These results support previous studies (Burkett, Kohrt, & Buchbinder, 1985; Catlin, 1979; Divert et al., 2008; Hanson, Berg, Deka, Meendering, & Ryan, 2011; Lussiana, Fabre, Hebert-Losier, & Mouro, 2013; Sobhani et al., 2013; Soule & Goldman, 1969; Squadrone & Gallozzi, 2009; Warne & Warrington, 2012) reporting running barefoot or in minimal shoes to be more economical than running in standard shoes. However, cushioning and other features of shoe design besides weight have been shown to have significant effect on running economy (Frederick, 1984). For example, the aerobic demand during treadmill running was about 2.8% less when running in well cushioned shoes compared with poorly cushioned shoes of similar mass (Frederick, 1984).

2.5.1.2 Limb Length

While lower limb mass distribution has been shown to affect running economy, there is no consensus on whether leg length is a factor in determining running economy. Leg length contributes to angular inertia and the metabolic cost of moving

legs during running (Anderson, 1996), and while there has been some research focusing on the relationship between leg length and stride length (Cavanagh & Kram, 1989; Elliott & Blanksby, 1979), the influence of leg length on economy has only been investigated indirectly. Research examining the physiques of male and female sprinters, middle-distance and long-distance runners have characterized sprinters as short-legged and middle- and long-distance runners as long-legged (Malina, Harper, Avent, & Campbell, 1971). In general middle- and long-distance runners have been found to exhibit better economy than sprinters (Bourdin et al., 1993; Daniels & Daniels, 1992; Kaneko, 1990; Pollock, 1977), however the influence of leg length on these differences is unknown. Myers and Steudel (1985) suggest that for a given body mass, speed and gait pattern, runners that are smaller and have proportionately greater amount of body mass distributed proximally in the legs perform less work to accelerate and decelerate the limbs (Myers & Steudel, 1985). However, despite Williams and Cavanagh (1987) finding a large variation in running economy among 31 male distance runners (Williams & Cavanagh, 1987), there were no differences associated with segmental leg lengths and masses.

2.5.1.3 Achilles Moment Arm

The amount of energy stored in a tendon depends on the mechanical properties of the tendon and on the forces that stretch the tendon. Thus, for a given kinematic pattern, and hence kinetic pattern, tendon force is inversely related to the moment arm of the Achilles tendon (Scholz et al., 2008). Since it is generally accepted that storage and reutilization of elastic energy in tendons substantially reduces energy demands in running (Cavagna & Kaneko, 1977) previous research has been able to establish a moderate (Raichlen, Armstrong, & Lieberman, 2011) to large (Scholz et al., 2008) (Figure 5) relationship between the variation in running economy and the moment arm of the Achilles tendon, albeit in small sample sizes of 8 to 15 (Raichlen et al., 2011; Scholz et al., 2008). Achilles tendon length and less flexible lower limb joints are associated with improved running economy (Hunter et al., 2011).

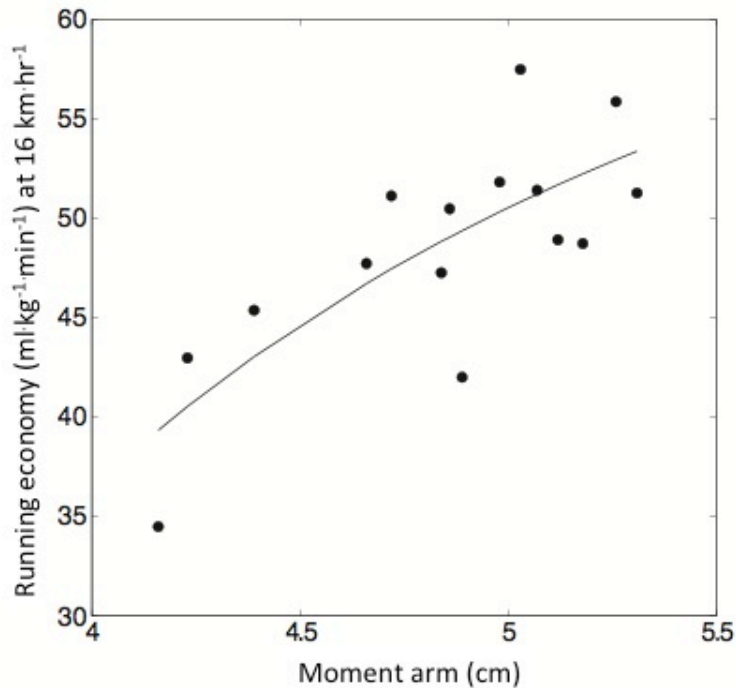


Figure 5: Relationship between moment arm length and running economy at 16 km.hr⁻¹ ($r = 0.77$). Adapted from Scholz et al (2008) (Scholz et al., 2008).

Other anthropometric characteristics throughout the body have also been investigated. Foot length has been found to be negatively correlated with running economy in elite male runners (Williams & Cavanagh, 1986). Pelvic and shoulder width could theoretically have an influence on running economy (Anderson, 1996) but have been studied very little with available evidence suggesting either no relationship (Anderson & Tseh, 1994; Williams & Cavanagh, 1987), or a moderate negative correlation between pelvic width and running economy (Williams & Cavanagh, 1986). The only postural characteristic that has been investigated relative to running economy is trunk angle or degree of forward lean while running. When comparing distance runners grouped by running economy, Williams and Cavanagh (1987) found that the most economical group displayed a slightly greater forward lean (5.9°) compared with the middle (3.3°) and least (2.4°) economical groups (Williams & Cavanagh, 1987).

2.5.2 Running Style / Gait Patterns

There is a belief amongst practitioners that, over time, runners adopt their most economical running style (Moore, Jones, & Dixon, 2012; Nelson & Gregor, 1976). Accordingly, high training volumes and the number of years of running experience have been suggested to be important for improved running economy (*See Training History and Volume below*) (Morgan et al., 1995). Indeed, a number of studies show that individuals tend to freely choose their most economical gait pattern (Cavagna, Willems,

Franzetti, & Detrembleur, 1991; Cavanagh & Kram, 1985a; Cavanagh & Williams, 1982; Kaneko, Matsumoto, Ito, & Fuchimoto, 1987; Knuttgen, 1961). While studies have identified small to moderate relationships between biomechanical characteristics and running economy (Cavanagh & Williams, 1982; Kaneko et al., 1987; McCann & Higginson, 2008; Nummela, Keranen, & Mikkelsen, 2007; Nummela, Rusko, & Mero, 1994; Tartaruga et al., 2012; Williams & Cavanagh, 1987), stride length is one of the few gait variables that has been shown by direct experimental evidence to affect economy (Cavanagh & Williams, 1982; Hogberg, 1952; Morgan, Martin, et al., 1994; Morgan & Martin, 1986).

2.5.2.1 Stride Length

Results from a number of studies (Cavanagh & Williams, 1982; Hogberg, 1952; Kaneko et al., 1987; Knuttgen, 1961; Powers, Hopkins, & Ragsdale, 1982) have indicated that submaximal VO_2 increases curvilinearly as stride length is either lengthened or shortened from that self-selected by the runner. This basic curvilinear relationship between stride length and economy has also been shown for walking (Dicharry, 2010) and racewalking (Morgan & Martin, 1986). The basic assumption behind this research appears to be that strides which are too long will require considerable power during propulsion, excessive vertical oscillation of the center of mass, produce a foot strike position which creates large braking forces and require joint ranges of motion which invoke increased internal friction and stiffness (Anderson, 1996). Conversely, strides that are too short would increase internal work through increased frequency and reciprocal movements (Anderson, 1996).

Hogberg (1952) was the first to indicate that well-trained runners at 14 and 16 $km \cdot h^{-1}$ are most economical at their own self-selected stride length versus running at stride lengths short and longer than the self-selected value (Hogberg, 1952). A comparison of the aerobic demands associated with these various stride length conditions revealed that VO_2 while running with a stride length ~13% longer than optimal was ~12% higher, while in contrast, a nearly equal decrease in stride length from optimal resulted in a 6% increase in VO_2 . More recent work has confirmed that VO_2 was lowest at stride lengths close to the self-selected condition and that a curvilinear relationship between stride length and VO_2 when evaluating seven stride length conditions at 13.8 $km \cdot h^{-1}$ for 10 well-trained runners (Cavanagh & Williams, 1982). Based on these results, Cavanagh and Williams (1982) concluded that there is little need to dictate stride length for most runners since they already tend to display near optimal stride lengths (Cavanagh & Williams, 1982). They proposed two mechanisms for this phenomenon. First, runners naturally acquire an optimal stride

length and stride rate over time, based on perceived exertion (Williams & Cavanagh, 1987), which supports the premises put forth previously (Morgan et al., 1995; Nelson & Gregor, 1976; Williams & Cavanagh, 1987). Second, runners may adapt physiologically through repeated training at a particular stride length/stride rate for a given running speed (Cavanagh & Williams, 1982).

Stride length and running economy have been shown to differ between experienced and novice runners, with experienced runners tending to possess longer stride lengths and better running economy (Chen, Nosaka, Lin, Chen, & Wu, 2009; Dallam, Wilber, Jadelis, Fletcher, & Romanov, 2005; Dillman, 1975), although Bailey and Messier (1991) found that neither stride length or running economy changed significantly over a seven-week training period in novice runners (Bailey & Messier, 1991). It has previously been suggested that it may take several months, if not years for changes in stride length and running economy to occur (Bailey & Pate, 1991).

Relationships between stride length and a variety of anthropometric dimensions have been low to moderate, but do show a tendency for people who are taller, longer legged, heavier and heavier legged and have limbs with greater moments of inertia to take longer strides (Williams & Cavanagh, 1987). Relationships between stride length and anthropometric characteristics expressed relative to height or leg length have also been low to moderate (Cavanagh & Williams, 1982; Kaneko et al., 1987; Williams & Cavanagh, 1987).

2.5.2.2 Stride Rate

Kaneko et al. (1987) suggested that the link between stride rate and economy may be associated with muscle fiber recruitment (Kaneko et al., 1987). At slower stride rates (and longer stride lengths), the muscles need to develop relatively high external power during propulsion to overcome large braking forces. Conversely at fast stride rates (short stride lengths), the mechanical power associated with moving the limbs increases due to increased frequency of reciprocal movements. They indicated that these extreme conditions may require a greater reliance on less economical Type II fibers than more intermediate stride rate/stride length combinations (Kaneko et al., 1987). Consequently, efforts to improve running economy via stride rate manipulation would be ineffective, unless the runner's freely chosen stride rate is not economically optimal (Bailey & Pate, 1991). However, Morgan et al. (1994) demonstrated that it was possible to train runners who self-selected an uneconomical over-striding rate to run at a stride rate closer to one predicted to be optimal, with a concomitant improvement in running economy (Morgan, Martin, et al., 1994).

2.5.2.3 Vertical Oscillations

Studies comparing the biomechanical characteristics of elite and good runners, found that elite distance runners have slightly less vertical oscillation and had better running economy than good runners (Cavagna et al., 2005; Cavanagh et al., 1977; Svedenhag & Sjodin, 1984; Tartaruga et al., 2012). Similarly, Williams and Cavanagh (1987) showed a trend, although nonsignificant, towards less vertical oscillation and better running economy (Williams & Cavanagh, 1987). The intuitive perception is that vertical oscillation is adversely related to economy; however, Cavagna et al. (2005) reported that less vertical oscillation results in high stride frequency and higher internal work to accelerate lower limb segments, thus increasing oxygen demand and reducing running economy (Cavagna et al., 2005). Conversely, Halvorsen et al. (2012) showed that reducing vertical oscillation has a positive effect on running economy (Halvorsen, Eriksson, & Gullstrand, 2012). These results suggest there is likely an optimal degree of vertical lift in order for stride length and other stride characteristics to not adversely affect running economy. To our knowledge, no research has investigated this possibility.

2.5.2.4 Footstrike Patterns

It continues to be argued that a forefoot strike pattern during running is more economical than a rearfoot pattern; however, previous studies using one habitual footstrike group have found no difference in running economy between footstrike patterns (Di Michele & Merni, 2013; Nilsson & Thorstensson, 1987; Williams & Cavanagh, 1986). In fact, Gruber et al. (2013) found no differences in VO_2 between 19 habitual forefoot runners and 18 habitual rearfoot runners (Gruber, Umberger, Braun, & Hamill, 2013). However, when subjects ran with the alternative footstrike pattern, VO_2 increased significantly (5.5%, $p < 0.001$) with the forefoot pattern but not the rearfoot pattern. Contrary to popular belief, these results suggest that the forefoot pattern is not more economical than the rearfoot pattern. There have also been no consistent findings between contact times and flight times, with some studies indicating longer contact times were associated with poorer economy (Tartaruga et al., 2012; Williams & Cavanagh, 1986; Williams & Cavanagh, 1987), shorter contact times were associated with worse economy (Chapman et al., 2012) and others finding no relationship (Cavanagh et al., 1977; Williams et al., 1987). Di Michelle and Merni (2013) suggest that with the aim of maximizing running economy, a trade-off between a midfoot strike pattern and a long contact time must be pursued (Di Michele & Merni, 2013).

2.5.3 Kinematics and Kinetics

While stride length, stride rate and other gait related characteristics have been

associated with running economy, other kinematic and kinetic factors such as angular velocities of limb segments and joints (Anderson & Tseh, 1994; Cavanagh et al., 1977; Tartaruga et al., 2012; Williams & Cavanagh, 1986; Williams & Cavanagh, 1987; Williams et al., 1987) and ground reaction forces (Chang & Kram, 1999; Farley & McMahon, 1992; Heise & Martin, 2001; Kram & Taylor, 1990) have also demonstrated a relationship with running economy.

2.5.3.1 Lower Body Kinematics

Comparisons of elite and good distance runners indicate that better economy in elite runners was associated with greater maximal angle of the thigh during hip extension, more extended lower leg at foot strike, more acute knee angles during swing and toe-off and that good runners plantar flexed an average of 10° more during toe-off than elite runners (Cavanagh et al., 1977; Williams & Cavanagh, 1986; Williams et al., 1987). Whereas running with experimentally increased knee flexion ('Groucho running') has been shown to increase the oxygen demand of running by as much as 50% (McMahon, Valiant, & Frederick, 1987). Williams and Cavanagh (1986) found that greater maximal plantar flexion velocity and greater horizontal heel velocity at foot strike were associated with better running economy in elite male distance runners (Williams & Cavanagh, 1986). These authors also reported that a lower velocity of the knee joint during the first half of foot contact was the only kinematic variable of 14 tested to be related to better economy (Williams & Cavanagh, 1987). However, in a study of elite female distance runners, better economy was associated with slower thigh extension velocity and lower knee flexion velocity during swing (Williams et al., 1987), suggesting that there is a gender specific optimal kinematic patterns. All of these relationships between economy and joint angles and velocities were trivial to moderate in strength.

In a study comparing three groups of runners grouped by varying levels of economy, Williams and Cavanagh (1987) reported that better economy was associated with shank angles of greater deviation from vertical at heel strike, less plantar flexion at toe off and more acute knee angle during mid-support (Williams & Cavanagh, 1987). Whereas, Paulson et al. (2013) and Kyrolainen et al. (2001) reported that angular velocities of the ankle, knee and hip joints were not good predictors of running economy (Kyrolainen et al., 2001; Paulson & Braun, 2013).

2.5.3.2 Upper Body Kinematics

Most investigations of running economy and running mechanics have focused on the kinematics of lower limbs with only a few studies (Anderson & Tseh, 1994;

Tartaruga et al., 2012; Williams & Cavanagh, 1986) considering the upper body limbs. Anderson and Tseh (1994) found no relationship between running economy and shoulder width, hip width, or ratio of shoulder to hip width (Anderson & Tseh, 1994). Whereas Williams and Cavanagh (1986) found a moderate negative correlation between shoulder to pelvic width and running economy in elite male runners (Williams & Cavanagh, 1986), indicating that the moments and forces generated by counter-rotations of the shoulders and hips and movements of the arms may affect running economy (Cappozzo, 1983a, 1983b; Hinrichs, 1990). Accordingly, a positive correlation between economy and angular velocity of shoulder rotation and angular displacement of the hips and shoulders about the polar axis of the trunk (Anderson & Tseh, 1994), as well as a negative correlation between economy and angular displacement of the shoulder in the sagittal plane has previously been described (Anderson & Tseh, 1994). However, Tartaruga et al. (2012) found no relationship between velocity changes of the wrists and shoulders or rotation of the hips and shoulders relative to the polar axis of the trunk and economy (Tartaruga et al., 2012). Some results have shown less arm movement, as measured by wrist excursion during the gait cycle, tended to reduce total upper body excursion from the body center of mass both laterally and horizontally and be associated with better running economy (Anderson & Tseh, 1994; Hinrichs, 1990; Tartaruga et al., 2012; Williams & Cavanagh, 1987).

2.5.3.3 Kinetics / Ground Reaction Forces

Investigations related to kinetics and running economy are limited and most work has focused on vertical ground reaction forces. Kram and Taylor (1990) presented a simple inverse relationship between the aerobic demand during running and the time the foot applies force to the ground during each stride, independent of body mass, indicating that the energy demand during running is determined by the cost of supporting one's body mass and the time course of generating force (Kram & Taylor, 1990). Williams and Cavanagh (1987) surmised that more economical runners have identifiable kinetic patterns in their running style, which are identifiable by lower first peaks for the vertical component of ground reaction forces, smaller antero-posterior and vertical peak forces, and greater energy transfer between upper and lower body segments (Williams & Cavanagh, 1987). They observed moderate and large correlations between ground-support time and peak medial forces with running economy, respectively (Williams & Cavanagh, 1986). Similarly, Heise and Martin (2001) also observed large correlations between ground reaction forces (total vertical impulse and net vertical impulse) and submaximal VO_2 (Heise & Martin, 2001), indicating less economical runners exhibit greater wasteful vertical motion. However,

similar data collected from elite male and female distance runners showed relatively low correlations between ground reaction forces and running economy (Williams & Cavanagh, 1986; Williams et al., 1987) suggesting that ground reaction forces are not likely to be the determining factor that makes one runner more economical than another, and that in fact some elite runners are economical despite poor ground reaction forces.

While vertical ground reaction forces have been shown to affect the metabolic demand during running in recreational and moderately trained runners due to the requirement to support body mass (Chang & Kram, 1999; Farley & McMahon, 1992; Heise & Martin, 2001; Kram & Taylor, 1990), horizontal forces can also substantially affect running economy. For example, in 25 well-trained endurance athletes, Nuumela et al. (2007) reported mass-specific horizontal forces were substantially related to running economy at five different running speeds (Nuummela et al., 2007). Similarly, Storen et al. (2011) found that the sum of horizontal and vertical peak forces were inversely correlated with running economy ($r = 0.66$) (Storen, Helgerud, & Hoff, 2011). Although only indirect links between horizontal (and vertical) kinetic forces and running economy can be made, the effects of air and wind resistance also affect running economy. Air resistance accounts for between 2-8% of the total energy demand of running during events ranging from 5,000 m to the marathon (Davies, 1980a; Pugh, 1970), while energy savings associated with drafting 1-2 m behind another runner have been estimated to be 3-6% (Kyle, 1979; Pugh, 1971). In general the detrimental effects of running into a head wind outweigh the benefits of running with a tail wind. For example, when horizontal force was altered to both impede and assist runners using an elastic rope systems, a 30% increase in aerobic demand was observed with a 6% impeding force and a 33% reduction with a 15% assisting force (Chang & Kram, 1999). Other studies have also observed an increase in aerobic demand of running proportional with the increase in external work (Cooke et al., 1991; Lloyd & Zacks, 1972; Zacks, 1973). Using a wind tunnel to apply horizontal impeding force, Pugh (1971) showed the aerobic demand of running increased with the square of the head wind velocity (Pugh, 1971). According to previous data, generating horizontal propulsive forces constitutes more than one-third of the total metabolic demand of running (Chang & Kram, 1999), therefore the horizontal and vertical kinetic forces related to running economy should be considered for future research. There has also been no research related to the moments and forces generated by counter-rotations of the hips and shoulders and running economy.

In summary, while some studies have identified small to large relationships

between biomechanical factors and running economy, overall the data are mostly conflicting preventing any clear conclusions. It does appear that runners with a high ponderal index, narrow pelvis, long slender legs with mass distribution closer to the torso, short Achilles moment arm, and shorter than average feet have better running economy. However, there does not appear to be any easily identifiable and universally applicable patterns of 'efficient' movement that will apply to all runners. Rather, it is likely that adjusting a given biomechanical characteristic may result in an economy enhancement in one athlete but the same adjustment in another might be uneconomical because of differences in anthropometric dimensions, running style, or other factors (Williams, 2007; Williams & Cavanagh, 1987). Perhaps a more promising avenue of research may be to concentrate on the individual runner in an effort to best identify how that athlete's structure and functional abilities influence running economy, subsequent performance as well as injury susceptibility.

2.6 Neuromuscular Efficiency

In addition to metabolic, cardiorespiratory, and biomechanical factors, neuromuscular characteristics are also important aspects of running economy. The interaction between the neural and muscle systems (i.e. neuromuscular system) is fundamental to all movement, and effectively translates cardiorespiratory capacity into efficient mechanics and therefore into performance. It is becoming more evident that aerobic factors are not the only variables that affect endurance performance (Bonacci et al., 2009). In fact, Green and Patla (1992) suggest that any failure of the contractile machinery could prevent full utilization of available oxygen (Green & Patla, 1992), suggesting that in some cases, the ability to use available oxygen might not be the limiting factor in endurance performance. For example, in ultra-endurance events, runners often experience neuromuscular fatigue causing them to slow before oxygen utilization is compromised (Davies & Thompson, 1979).

Neuromuscular characteristics are related to the activation, recruitment and excitation properties, of the motor unit or muscle group as a whole. These characteristics may include neural activation, motor unit synchronization, muscle force, stored elastic energy, stiffness, power, ground contact time, and/or the excitation/contraction coupling sequence (Green & Patla, 1992; Hakkinen, 1994; Hakkinen, Komi, & Alen, 1985; Nummela et al., 2006; Paavolainen, Nummela, Rusko, et al., 1999; Paavolainen, Nummela, & Rusko, 1999; Sale, 1988). Essentially neuromuscular efficiency can be divided into two categories: 1) factors that improve the neural signaling and motor programming of the running motion and 2) those that improve the muscle force production itself.

2.6.1 Neural Signaling and Motor Programming

High performance running is a skill, much like hitting a golf ball or shooting a basketball, that requires precise timing of nearly all the major muscles and joints in the body to convert muscular force in translocation (Anderson, 1996). Similar to those skills, practice is needed to improve the efficiency at the activity. Motor learning studies have shown that continued practice of a task results in more skilled control of movement, characterized by decreased amplitude and duration of muscle activity, decreased muscle co-activation and less variability of movement (Osu et al., 2002; Thoroughman & Shadmehr, 1999; Wang et al., 1993). Recent evidence has shown that recreational runners ($3.4 \pm 2.8 \text{ km}\cdot\text{wk}^{-1}$) exhibited greater individual variance (i.e. variability between strides), greater population variance (i.e. variability of muscle recruitment between athletes), more extensive and more variable muscle co-activation and longer durations of muscle activity than moderately trained runners (6.6 ± 1.4 years of running experience, who ran $61.4 \pm 8.8 \text{ km}\cdot\text{wk}^{-1}$) (Chapman, Vicenzino, Blanch, & Hodges, 2008a). These findings are consistent with previous short-term training studies of arm, hand and leg (pedaling) movements (Chapman, Vicenzino, Blanch, & Hodges, 2009; Chapman, Vicenzino, Blanch, & Hodges, 2007, 2008b; Osu et al., 2002), suggesting that ongoing neuromuscular adaptations occur as a result of continued training. It is apparent within the literature that run training can induce positive changes in running economy (Bransford & Howley, 1977; Daniels & Oldridge, 1971; Dolgener, 1982). Running also appears to induce adaptations in motor programming and recruitment (Osu et al., 2002; Thoroughman & Shadmehr, 1999). It has recently been hypothesized that improvements in running economy following various training modalities such as resistance training and plyometric or explosive resistance-training were due to neuromuscular adaptations (Barnes, Hopkins, McGuigan, Northuis, et al., 2013; Johnston et al., 1997; Jung, 2003; Paavolainen, Hakkinen, et al., 1999). Inferences have also been made that optimal lower-limb muscle recruitment is critical for superior running economy (Anderson, 1996). If neuromuscular adaptations are responsible for the changes in running economy then it would be reasonable to suggest that there would be alterations in neural signaling during running following training. Bonacci et al. (2009) advocate that adaptations to motor recruitment as a result of training represent a learning effect (Bonacci et al., 2009). Positive adaptations infer that an individual learns to produce specific patterns of muscle recruitment that are associated with improved efficiency of the task (e.g. improved biomechanical and neuromuscular efficiency) resulting in enhanced performance (Bonacci et al., 2009).

2.6.2 Muscle Force Production and Stiffness

There are two muscle contraction-related issues that potentially influence energy demand and running economy; velocity of contraction and balance between concentric and eccentric contractions. With regards to velocity contraction, Taylor (1994) has observed that it is less costly for muscles to generate force at low velocities, that force is highest and metabolic rate lowest during isometric contraction, and that the energy cost of generating force increases dramatically with greater shorting velocity (Taylor, 1994). Based on this finding, it has been hypothesized that muscles produce economic force rather than efficient work during running. The proposed mechanism for this is that muscle contractions are primarily isometric, adjusting the stiffness of the muscle-tendon unit during the eccentric phase to produce simultaneous deceleration and elastic stretch, then producing a nearly isometric impulse that initiates ballistic concentric acceleration. This proposed mechanism would promote optimization by exploitation 'free' elastic energy, and minimizing metabolic requirements. Such optimization would obviously demand precise timing, and integration and refinement of the temporal, kinetic and kinematic patterns, which would require considerable practice and training.

2.6.2.1 Muscle Power

It has been suggested that endurance performance may be limited not only by aerobic power but also by 'muscle power' factors related to the force and velocity characteristics of the neuromuscular system (Noakes, 1988). Indeed, performance during a 5-km and 10-km run has been shown to be partially determined by neuromuscular characteristics and muscle power, suggesting that skeletal muscle contractility differs between fast and slow runners (Noakes, 1988; Paavolainen, Hakkinen, et al., 1999; Paavolainen, Nummela, & Rusko, 1999). Similarly, in a homogenous group of highly trained endurance runners with similar VO_{2max} values, those athletes with faster 10-km and 5-km run times displayed higher relative muscle pre-activation (prior to touchdown), accompanied with lower relative integrated electromyographic (iEMG) activity during the propulsion phase, along with shorter stance phase contact times than those athletes with slower run times (Paavolainen, Nummela, Rusko, et al., 1999; Paavolainen, Nummela, & Rusko, 1999). Furthermore, there was a significant correlation between running economy and mean stance phase contact times during constant velocity running, suggesting muscle power characteristics play an important role in determining distance running performance in highly trained runners (Paavolainen, Nummela, & Rusko, 1999).

2.6.2.2 Stiffness

It is possible that shorter stance phase contact times and greater muscle pre-activation may represent enhanced leg muscle stiffness, leading to faster transition from the braking to propulsive phase of ground contact (Nummela et al., 2008; Paavolainen, Nummela, Rusko, et al., 1999). Dalleau et al. (1998) highlighted the importance of neuromuscular factors by demonstrating that running economy was related to the stiffness of the propulsive leg, with greater stiffness eliciting the best running economy (Dalleau, Belli, Bourdin, & Lacour, 1998). Arampatzis et al. (2006) corroborate this finding such that in a group of 28 long-distance runners separated into three groups by economy, the most economical runners had highest tendon stiffness (Arampatzis et al., 2006). Kubo et al. (2010) however the lower tendon stiffness was associated with better 5000-m running performance in long distance runners (Kubo, Tabata, Ikebukuro, Igarashi, Yata, et al., 2010). Leg stiffness is modulated by neuromuscular activation, and changes in stiffness have been shown to occur as a result of neuromuscular adaptation to training (e.g. learning of more efficient or more skilled patterns of motor recruitment) (Franklin, Burdet, Osu, Kawato, & Milner, 2003). In support of the association between motor recruitment and leg stiffness, a reduction in EMG pre-activation was shown to be significantly related to a decrease in post-landing leg stiffness following fatiguing exercise (Avela & Komi, 1998). Greater duration of muscle co-activation of bi-articular leg muscles during stance has also been significantly associated with better running economy (Heise, Shinohara, & Binks, 2008). Muscle co-activation modulates leg stiffness during running and may alter running economy through utilization of stored elastic energy, which has no additional metabolic cost. Albracht and Arampatzis (2013) indicated that increased tendon stiffness is indicative of greater energy storage and return and a redistribution of muscular output within the lower extremities while running (Albracht & Arampatzis, 2013), which might result in improved running economy. Running economy and stiffness have been shown to change together with training (Fletcher, Esau, & MacIntosh, 2010; Kubo, Tabata, Ikebukuro, Igarashi, & Tsunoda, 2010). It has also been shown that stiffness of the muscle-tendon unit increases with running speed (Cavagna & Kaneko, 1977; Morgan, Martin, et al., 1994; Saibene, 1990).

2.6.2.3 Stretch Shortening Cycle

Kyrolainen et al. (2001) found that as running speed increased so did EMG preactivation and ground reaction forces, along with their rate of force production (Kyrolainen et al., 2001). Preparatory muscle function is an important function of the stretch shortening cycle (SSC). The SSC is a combination of a high velocity eccentric contraction followed immediately with a concentric contraction. Stretch shortening

cycle muscle function enhances performance during the final phase (concentric action) (Nicol, Avela, & Komi, 2006), and the increase in preparatory muscle activity with higher running speeds was suggested to be a mechanism to tolerate higher impact loads, regulate landing stiffness (Gollhofer & Kyrolainen, 1991) and improve running economy (Kyrolainen et al., 2001). A recent study showed that a greater ratio of eccentric to concentric vastus lateralis muscle activity was associated with a lower metabolic demand during running (i.e. better running economy) (Abe, Muraki, Yanagawa, Fukuoka, & Niihata, 2007).

2.6.2.4 Elastic Energy Storage

The balance between eccentric and concentric contractions could potentially influence running economy, since the eccentric contractions during which elastic energy is stored are less costly than the concentric contractions in which the energy is released (Williams, 1985). There is clear evidence that the mechanical efficiency of running exceeds the efficiency of conversion of chemical energy to kinetic energy by muscles (Cavagna & Kaneko, 1977; Cavanagh & Kram, 1985a; Williams, 1985). Elastic energy stored during the eccentric contractions of running makes a substantial contribution to propulsion as it is released during subsequent concentric contractions (Aruin, Prilutskii, Raitsin, & Savel'ev, 1979; Cavagna & Kaneko, 1977). Unfortunately, there currently are no data available from which to quantify the relative energy cost of the two types of contractions nor has there been a method devised to differentiate true eccentric contractions from tendon stretching or to quantify the storage and release of elastic energy (Asmussen & Bonde-Petersen, 1974; Cavanagh & Kram, 1985a; Leger & Mercier, 1984; Luhtanen & Komi, 1978; Williams, 1985; Winter, 1978). There is however, consensus that this phenomenon contributes to both efficiency and economy of movement.

Both actomyosin cross-bridges and tendons have been implicated as important sites of energy storage (Cavagna & Citterio, 1974; Ker, Bennett, Bibby, Kester, & Alexander, 1987). Ker et al. (1987) have estimated that the Achilles tendon and tendons in the arch of the foot can store 35% and 17%, respectively, of the kinetic and potential energy gained and lost in a step while running at moderate speed (Ker et al., 1987). Alexander (1988) has shown that in a 70 kg human running at $\sim 16 \text{ km}\cdot\text{hr}^{-1}$, more than half of the elastic energy can be stored in just two springs, the Achilles tendon and the arch of the foot (Alexander, 1988). Cavagna et al. (1964) have estimated that VO_2 during running might be 30 to 40% higher without contributions from elastic storage and return of energy (Cavagna, Saibene, & Margaria, 1964). At higher running speeds, elastic recovery of energy prevails over the contractile machinery and

accounts for most of the work (Cavagna & Kaneko, 1977; Taylor, 1994). Elastic capacitance is influenced by the rate and magnitude of stretch, the level of activation and resulting stiffness of the muscle-tendon unit, muscle length at completion of the stretch and initiation of the succeeding concentric contraction (Aruin & Prilutskii, 1985; Aruin et al., 1979; Cavagna & Kaneko, 1977). The available evidence indicates that there may be substantial interindividual differences in ability to store and release elastic energy (Aura & Komi, 1986a; Ito, Komi, Sjodin, Bosco, & Karlsson, 1983; Williams & Cavanagh, 1983) and it has been suggested that fiber composition, gender and maturity are likely contributors to these differences (Aura & Komi, 1986b). It is obvious from the foregoing that the storage and release of elastic energy in muscles makes important contributions to running economy and may have potential to explain a considerable portion of the interindividual differences in economy.

Taken together, the findings from these studies suggest that neuromuscular efficiency may play an important role in determining running economy, especially in athletes with similar physiological attributes. Specifically, the timing and amplitude of muscle activity has been shown to have the most consistent association with running economy. Greater muscle activity prior to and in the initial phase of ground contact may enhance running economy by increasing leg stiffness and maximizing exploitation of stored elastic energy.

2.7 Conclusions and Future Directions

It is clear that running economy is a complex, multifactorial concept that represents the sum of metabolic, cardiorespiratory, biomechanical and neuromuscular efficiency during running. Therefore, the measure of running economy may inherently be flawed as it may or may not be based on oxygen consumption alone. While running economy has traditionally been measured in the laboratory, recent technological advances allow the possibility to obtain measurements during over-ground running using portable oxygen analyzers. Well-controlled reliability studies indicate the test-retest reliability of running economy is fairly stable suggesting researchers can be relatively confident in their measurements. A number of factors appear to effect running economy. However it seems likely that the running economy exhibited by a particular athlete reflects the integrated composite of a variety of metabolic, cardiorespiratory, biomechanical and neuromuscular characteristics that are unique to the individual. Of these factors, it seems that a few are subject to alteration or improvement through training or other interventions (Part II).

CHAPTER 3: STRATEGIES TO IMPROVE RUNNING ECONOMY

3.1 Abstract

Running economy represents a complex interplay of physiological and biomechanical factors (refer to Part I) that is represented by the energy demand for a given velocity of submaximal running and expressed as the submaximal VO_2 at a given running velocity. This review considered a wide range of acute and chronic interventions that have been investigated with respect to improving economy by augmenting one or more components of the metabolic, cardiorespiratory, biomechanical or neuromuscular systems. Improvements in running economy have traditionally been achieved through endurance training. Endurance training in runners leads to a wide range of physiological responses and it is very likely that running training characteristics influence running economy. Training history and training volume have been suggested to be important factors in improving running economy, while uphill and level-ground high-intensity interval training represent frequently prescribed forms of training that may elicit further enhancements in economy. More recently, research has demonstrated short-term resistance and plyometric training has resulted in enhanced running economy. This improvement in running economy has been hypothesized to be a result of enhanced neuromuscular characteristics. Altitude acclimatization results in both central and peripheral adaptations that improve oxygen delivery and utilization, mechanisms that potentially could improve running economy. Other strategies, such as stretching should not be discounted as a training modality in order to prevent injuries, however, it appears that there is an optimal degree of flexibility and stiffness required to maximize running economy. Several nutritional interventions have also received attention for their effects on reducing oxygen demand during exercise, most notably dietary nitrates and caffeine. It is clear that a range of training and passive interventions may improve running economy and researchers should concentrate their investigative efforts on more fully understanding the types and mechanisms which affect running economy and the practicality and extent to which running economy can be improved outside the laboratory.

3.2 Introduction to Strategies to Improve Running Economy

The goal in competitive distance running is to run a given distance in the least time, or at least faster than the next best competitor. A number of physiological attributes contribute to successful distance running performance, including (i) both a high cardiac output and a high rate of oxygen delivery to working muscles, which leads to a large capacity for aerobic adenosine triphosphate (ATP) regeneration [(i.e. high maximal oxygen uptake $VO_2\text{max}$)] (Foster & Lucia, 2007; Pollock, 1977); (ii) the ability to sustain a high percentage of $VO_2\text{max}$ for long periods of time (i.e. fractional utilization of $VO_2\text{max}$, relative intensity) (Costill et al., 1973); and (iii) the ability to move efficiently (running economy) (Bailey & Pate, 1991; Daniels, 1974a, 1985). Maximal aerobic capacity and fractional utilization of $VO_2\text{max}$ have been widely studied as determinants of running performance, however, running economy has been relatively ignored until the past decade or so despite being aware of its importance since at least the 1970's (Foster & Lucia, 2007).

Trained runners have superior running economy to lesser-trained or untrained runners (Bransford & Howley, 1977; Daniels, Oldridge, et al., 1978; Dolgener, 1982), indicating positive adaptations occur in response to habitual training (Beneke & Hutler, 2005). While a given athlete may be genetically predisposed to having 'good' running economy (see Part I), various strategies can potentially further improve an individual's running economy through augmenting metabolic, cardiorespiratory, biomechanical and/or neuromuscular responses and adaptations. Given running economy has been identified as a critical factor contributing to distance running performance (Conley & Krahenbuhl, 1980; Conley et al., 1984; Costill, 1967; Costill et al., 1973; Daniels, 1974a; Daniels & Daniels, 1992; di Prampero et al., 1993; Jones, 2006; Pollock, 1977) effective legal and practical strategies to improve running economy are sought after by coaches, athletes and sports scientists. To date, a wide range of acute and chronic interventions have been investigated with respect to improving economy including various forms of resistance training (Guglielmo et al., 2009; Johnston et al., 1997; Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006; Sedano et al., 2013; Spurrs et al., 2003; Storen et al., 2008; Taipale et al., 2009; Taipale, Mikkola, Salo, et al., 2013; Turner et al., 2003), high-intensity interval training (Billat et al., 1999; Denadai et al., 2006; Enoksen, Shalfawi, & Tonnessen, 2011; Franch et al., 1998; Sjodin et al., 1982), altitude exposure (Burtscher, Gatterer, Faulhaber, Gerstgrasser, & Schenk, 2010; Katayama, Matsuo, Ishida, Mori, & Miyamura, 2003; Katayama et al., 2004; Levine & Stray-Gundersen, 1997; Neya, Enoki, Kumai, Sugoh, & Kawahara, 2007; Saunders, Telford, et al., 2004; Saunders, Telford, Pyne, Hahn, & Gore, 2009; Schmitt

et al., 2006), stretching (Craib et al., 1996; Gleim, Stachenfeld, & Nicholas, 1990; Godges, Macrae, Longdon, Tinberg, & Macrae, 1989; Hunter et al., 2011; Jones, 2002; Mojock, Kim, Eccles, & Panton, 2011), as well as nutritional supplements (Figure 6) (Beis, Polyviou, Malkova, & Pitsiladis, 2011; Birnbaum & Herbst, 2004; Jones, 2013; Lansley, Winyard, Fulford, et al., 2011; Whitehead, Martin, Scheett, & Webster, 2012). Several other areas have been previously identified as feasible strategies to improve running economy, such as training in the heat (Bailey & Pate, 1991; Saunders, Pyne, et al., 2004a; Svedenhag, 2000) or cold and training surface, but have yet to be examined in the literature. Therefore, the purpose of this review is to examine various training strategies that have attempted to improve running economy, discuss the feasibility of strategies previously identified but yet to be explored in the literature, and discuss potentials areas for future research.

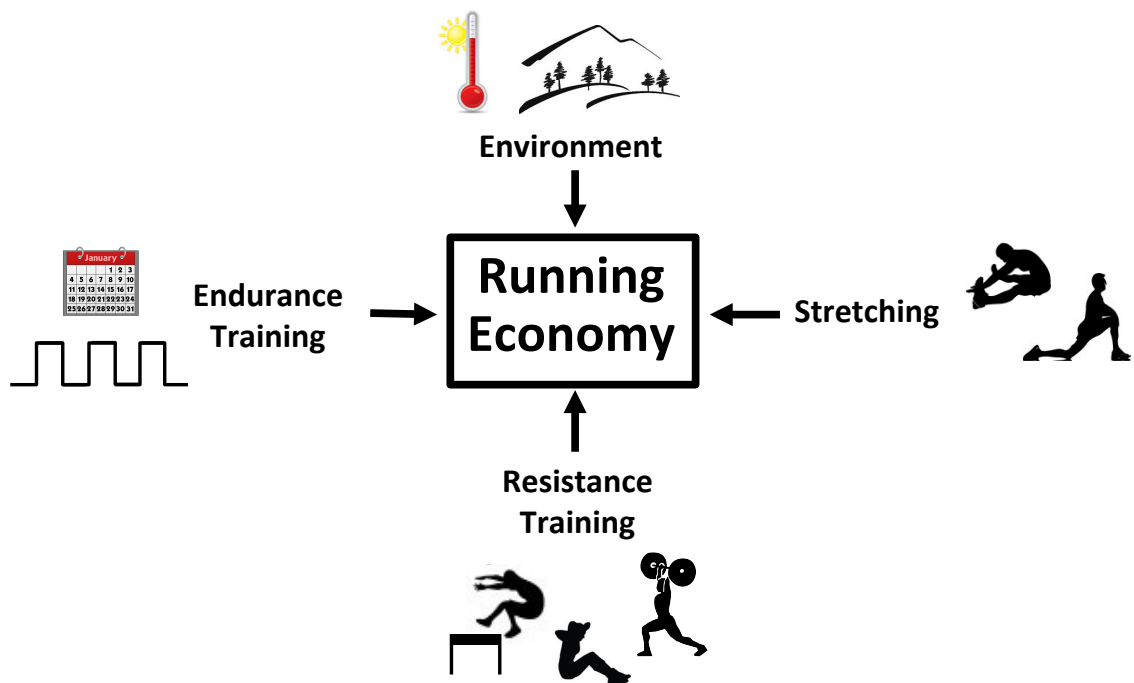


Figure 6: Schematic of strategies to improve running economy.

3.3 Endurance Training in Runners

A range of physiological responses occur in response to endurance training in runners and it is very likely that running training characteristics influence running economy. Endurance training leads to increases in the morphology and functionality of skeletal muscle mitochondria (Holloszy, Rennie, Hickson, Conlee, & Hagberg, 1977; Saunders, Pyne, et al., 2004a). Specifically, an increase in the oxidative muscle capacity allows trained runners to use less oxygen per mitochondrial respiratory chain during submaximal running (Assumpcao Cde, Lima, Oliveira, Greco, & Denadai, 2013).

Furthermore adaptations such as improved skeletal muscle buffer capacity (Gore et al., 2001) and hematological changes (Burtscher, Nachbauer, Baumgartl, & Philadelphy, 1996; Levine & Stray-Gundersen, 1997) (i.e. increased red cell mass) have been observed following various training modalities. These adaptations could also invoke improvements in oxygen delivery and utilization that could improve an athlete's running economy. While training has been suggested to invoke a range of central and peripheral adaptations that improve the metabolic and cardiorespiratory efficiency of a runner (Green, 2000; Green et al., 2000), many of these adaptations are largely governed by the training load which can be manipulated for a given athlete by increasing the volume or intensity of running over time.

3.3.1 Training History

Successful endurance runners typically undergo several years of training to enhance the physiological characteristics important to determining success in distance running events. Indeed, the number of years of running experience and high training volumes has been suggested to be important to running economy (Morgan et al., 1995; Nelson & Gregor, 1976). Unfortunately the few longitudinal studies that have examined this questions have yielded little consensus, with findings indicating no change (Daniels, Yarbrough, et al., 1978; Wilcox & Bulbulian, 1984), a slight increase (Lake & Cavanagh, 1990), and varying degrees reductions (1-15%) in submaximal VO_2 among trained and untrained runners engaging in different combinations of years, distance, interval and uphill training (Conley, Krahenbuhl, & Burkett, 1981; Patton & Vogel, 1977; Sjodin et al., 1982; Svedenhag & Sjodin, 1984). For example, in moderately trained runners, Mayhew et al. (1979) found that years of training was significantly correlated ($r = 0.62$) with running economy (Mayhew, Piper, & Etheridge, 1979). In support, Midgley et al. (2007) has suggested that the most important factor in improving running economy may be the cumulative distance a runner has run over years of training and not training volume *per se* (Midgley et al., 2007). This may be due to continued long-term adaptations in metabolic, biomechanical and neuromuscular efficiency (Midgley et al., 2007; Nelson & Gregor, 1976). Case study data from world-class runners also suggests that running economy improves over several years of training (Conley et al., 1984; Daniels, 1974b; Ingham, Fudge, & Pringle, 2012; Jones, 1998, 2006), however it's unclear of the role and interaction of training volume and consistency of training in such improvements over several years of training.

3.3.2 Training Volume

The influence of training volume on running economy is not well discussed in the literature and unfortunately no training studies to date have examined the

implications of increased training volume while controlling for potential confounding variables like training intensity. This makes it difficult to ascertain the effects of manipulating training volume (Midgley et al., 2007). However, in a cross-sectional investigation, Pate et al. (1992) reported that training volume was not associated with better running economy (Pate et al., 1992). Nevertheless, the importance of training volume should not be downplayed, as high-volume training is important to inducing adaptations important to distance running success (Laursen, 2010). Clearly, there is a need for longitudinal examinations of the relationship between running economy and training history, including how subtle changes in volume, intensity, cumulative volume before conclusions about the cumulative effects of training volume can be made.

3.3.3 High-Intensity Interval Training (HIIT)

Studies that have incorporated flat overground high-intensity interval training (HIIT) into the training programs of distance runners have reported equivocal results in relation to improving running economy (Table 3). Jones and Carter (2000) suggested that runners are typically most economical at the running velocities at which they habitually train (Jones & Carter, 2000), however, no training study to date has investigated the specificity of training velocity on running economy. High-intensity interval training at 93–120% velocity at $VO_2\text{max}$ ($vVO_2\text{max}$) (Barnes, Hopkins, et al., 2013b; Billat et al., 1999; Franch et al., 1998; Laffite et al., 2003; Sjodin et al., 1982; Slawinski et al., 2001) and continuous running at velocity at the onset of blood lactate accumulation ($vOBLA$) (Barnes, Hopkins, et al., 2013b; Billat et al., 1999; Denadai et al., 2006; Sjodin et al., 1982) have both been shown to improve running economy by ~1-7% (Table 3). Other studies using similar training intensities have reported no significant improvement (Barnes, Hopkins, et al., 2013b; Franch et al., 1998; Smith, McNaughton, & Marshall, 1999; Yoshida et al., 1990). Morgan et al. (1989) suggested that the type of run training exerts a negligible effect on improving running economy, based on the observation that several studies reported no differences in changes in running economy despite the runners engaging in different interval training programs (Morgan, Martin, et al., 1989).

Whereas $VO_2\text{max}$ has been shown to increase significantly during the transition between the off-season and pre-competitive period, during which training intensity is increased (Brisswalter & Legros, 1994b; Conley et al., 1984; Svedenahg & Sjodin, 1985; Wilcox & Bulbulian, 1984), the same studies reported either a significant improvement (Conley et al., 1984; Svedenahg & Sjodin, 1985) or no change (Brisswalter & Legros, 1994b; Wilcox & Bulbulian, 1984) in running economy. Franch et al. (1998) compared interval training at 94%, 106% and 132% $vVO_2\text{max}$ and found

that running economy significantly improved in the 94% and 106% groups, but not in the group that trained at 132% $vVO_2\text{max}$ (Franch et al., 1998). This suggests that very high-intensity running is not effective in improving running economy, possibly due to a loss of running form at very high running velocities, or an inability to complete a sufficient training volume to elicit a training effect (Midgley et al., 2007).

Biomechanical changes could improve exercise efficiency following HIIT. However, Lake and Cavanagh (1996) investigated the effects of six weeks of high-intensity interval training on various biomechanical variables in a group of moderately trained runners and found no relationship between changes in performance, $VO_2\text{max}$, running economy and biomechanical variables (Lake & Cavanagh, 1996). The authors concluded that improvements in performance following HIIT were more likely to be caused by physiological rather than biomechanical factors.

Table 3: Comparison of effects on running economy and performance following adaptation to various high intensity interval-training (HIIT) interventions.

Study (year)	Subjects	Volume	Frequency and duration	Control	Results (%)	
					Running economy	Performance (distance)
Interval training						
Sjodin et al. (1982) (Sjodin et al., 1982)	8 highly trained male runners	20 min at $vOBLA$ ($vOBLA = 85\% vVO_2\text{max}$)	1 d/wk for 14 wk	No control	↑ 2.8	n/a
Yoshida et al. (1990) (Yoshida et al., 1990)	6 recreation female runners	20 min at $vOBLA$ ($vOBLA = 91\% vVO_2\text{max}$)	6 d/wk for 8 wk	Endurance training	↑ 2.8	n/a
Franch et al. (1998) (Franch et al., 1998)	12 recreational male runners	Continuous at 94% $vVO_2\text{max}$	3 d/wk for 6 wk	No control	↑ 3.1	↑ 94 (time to exhaustion at 87% $VO_2\text{max}$)
Franch et al. (1998) (Franch et al., 1998)	12 recreational male runners	4-6× 4min at 106% $vVO_2\text{max}$	3 d/wk for 6 wk	No control	↑ 3.0	↑ 67 (time to exhaustion at 87% $VO_2\text{max}$)
Franch et al. (1998) (Franch et al., 1998)	12 recreational male runners	30-40× 15 s at 132% $vVO_2\text{max}$	3 d/wk for 6 wk	No control	↑ 0.9	↑ 65 (time to exhaustion at 87% $VO_2\text{max}$)
Billat et al. (1999) (Billat et al., 1999)	8 highly trained male runners	4 wk: 5× 3 min at 100% $vVO_2\text{max}$; 2× 20 min $vOBLA$ ($vOBLA = 85\% vVO_2\text{max}$) 4 wk: 3× (5× 3 min at 100% $vVO_2\text{max}$); 2× 20 min $vOBLA$ ($vOBLA = 85\% vVO_2\text{max}$)	2 d/wk for 4 wk + 4 d/wk for 4 wk	No control	↑ 6.1 ↑ 7.7	↔ (time to exhaustion at MAS)
Slawinski et al. (2001) (Slawinski et al., 2001)	6 moderately trained runners	2× $v\Delta 50$ intervals); 3× continuous at 60-70% $vVO_2\text{max}$ ($v\Delta 50 = 93\% vVO_2\text{max}$)	2 d/wk for 8 wk	No control	↑ 3.6	↑ 17.3 (time to exhaustion at 17 $\text{km}\cdot\text{h}^{-1}$)
Laffite et al.	7 moderately	2× $v\Delta 50$ intervals	2 d/wk for 8	No control	↑ 5.4	n/a

(2003) (Laffite et al., 2003)	trained male runners	($v\Delta 50 = 93\%$ vVO_{2max})	wk				
Smith et al. (2003) (Smith, Coombes, & Geraghty, 2003)	18 moderately trained runners	6× 2 min vVO_{2max} + 1× continuous at 60% vVO_{2max}	2 d/wk for 4 wk	Endurance training	↑ 3.3	↑ 2.8 (3-km) ↑ 2.3 (5-km)	
Smith et al. (2003) (Smith et al., 2003)	18 moderately trained runners	5× 2.5 min vVO_{2max} + 1× continuous at 70% vVO_{2max}	2 d/wk for 4 wk	Endurance training	↔	↑ 1.0 (3-km) ↔ (5-km)	
Denadai et al. (2006) (Denadai et al., 2006)	9 moderately trained male runners	4× 60% t_{lim} at 95% vVO_{2max} ; 2× 20 min $vOBLA$	2 d/wk for 4 wk	No control	↑ 2.6	↔ (1500-m) ↑ 1.5 (5-km)	
Denadai et al. (2006) (Denadai et al., 2006)	8 moderately trained male runners	5× 60% t_{lim} at 100% vVO_{2max} ; 2× 20 min $vOBLA$	2 d/wk for 4 wk	No control	↑ 6.7	↑ 2.0 (1500-m) ↑ 1.4 (5-km)	
Enoksen et al. (2011) (Enoksen et al., 2011)	10 highly trained male runners	13% of total training volume at 82-92% HR_{max}	1 d/wk for 10 wk	No control	↑ 4.1	n/a	
Enoksen et al. (2011) (Enoksen et al., 2011)	9 highly trained male runners	33% of total training volume at 82-92% HR_{max}	3 d/wk for 10 wk	No control	↑ 2.6	n/a	

Highly trained = national/international level and $VO_{2max} > 65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; **moderately trained** = weekly running volume $> 30 \text{ km}\cdot\text{wk}^{-1}$; **recreational** = weekly running volume $< 30 \text{ km}\cdot\text{wk}^{-1}$; **reps** = repetitions; **RM** = repetition maximum; t_{lim} = time limit; vVO_{2max} = velocity at VO_{2max} ; $vOBLA$ = velocity at the onset of blood lactate accumulation; vLT = velocity at the lactate threshold; $v\Delta 50$ = velocity midway between vLT and vVO_{2max} ; ↑ indicates increase; ↔ indicates no change; ↓ indicates decrease; n/a indicates not measured.

3.3.3.1 Uphill Interval Training

Uphill running represents a frequently prescribed form of HIIT in periodized training programs for distance runners. For example, a survey of teams competing in a collegiate cross-country national championship race verified its widespread use as a training method and revealed that faster team times were correlated with uphill training (Kurz et al., 2000). Moreover, references to its potential effectiveness as a movement-specific form of resistance training have appeared in several reviews (Billat, 2001; Midgley et al., 2007; Saunders, Pyne, et al., 2004a) however, only anecdotal reports and limited research investigations (Barnes, Hopkins, et al., 2013b; Ferley et al., 2012; Houston & Thomson, 1977) exist concerning the physiological responses and potential improvements in performance to such training. Unlike other modes of resistance-training, where a transfer of learning would need to occur to improve running economy, uphill running is movement specific and the mechanisms for improving running economy are likely to directly affect one or more of the metabolic, biomechanical and neuromuscular systems.

It appears that further research is required to establish the relative efficacy of high-intensity interval training for improving the running economy of long-distance runners and to establish whether improvements in running economy can be derived from uphill and flat interval training through variations in the frequency, duration,

volume and periodization of training.

3.3.3.2 Training Surface

Running on grass, sand and other surfaces of varying compliance have been used by coaches and athletes as a supplemental training stimulus to HIIT on track or concrete surfaces for many years (McMahon & Greene, 1978, 1979; Pinnington & Dawson, 2001a). However despite the potential training benefits, no training studies have investigated the use of various surfaces such as sand running as a means to enhance running economy. Previous studies (Lejeune, Willems, & Heglund, 1998; Pinnington & Dawson, 2001a, 2001b; Zamparo, Perini, Orizio, Sacher, & Ferretti, 1992) have quantified the energy demand of running on sand to be 1.2-1.6 times the firm surface values at comparable running speeds. Pinnington and Dawson (2001) found that recreational runners running at 8 km·hr⁻¹ on grass recorded a relative VO₂ of 32.2 ml·kg⁻¹·min⁻¹ or approximately 56% of VO₂max compared to 47.0 ml·kg⁻¹·min⁻¹ or approximately 82% of VO₂max while running on soft, dry, beach sand at the same speed (Pinnington & Dawson, 2001a). Similarly, elite surf ironmen, who regularly train and perform in sand recorded VO₂ of 32.5 ml·kg⁻¹·min⁻¹ (50.6% of VO₂max) on grass compared to 43.3 ml·kg⁻¹·min⁻¹ (82% of VO₂max) on sand at 8 km·hr⁻¹ (Pinnington & Dawson, 2001b). Lejeune et al. (1998) attributed the increased energy demand of running on sand to a decrease in muscle-tendon efficiency (Lejeune et al., 1998), while Zamparo et al. (1992) credited the increased energy demand to a reduced recovery of potential and kinetic energy at each stride (approximately 45% to be compared to approximately 65% on a firm surface) and to a reduced recovery of elastic energy (Zamparo et al., 1992). In support, Impellizzeri et al. (2008) found that 4 weeks of plyometric training on sand improved both jumping and sprinting ability and induced less muscle soreness compared to on grass (Impellizzeri et al., 2008). Several other studies (Binnie, Dawson, Pinnington, Landers, & Peeling, 2013a, 2013b; Binnie, Peeling, Pinnington, Landers, & Dawson, 2013; Yigit & Tuncel, 1998) have demonstrated that acute and chronic training programs on sand result in a greater physiological responses than training on harder surfaces (e.g. grass, concrete) however, no direct measurements of running economy were made.

Taken together, despite the absence of data on the training effects of running surface on running economy, the available evidence suggests running in sand does elicit a greater metabolic response than running on hard surfaces perhaps due to a decrease in muscle tendon elasticity and stiffness and an impairment in SSC efficiency. It appears that training in sand may induce different neuromuscular and biomechanical adaptations as well (Pinnington, Lloyd, Besier, & Dawson, 2005), however the

implication for this on running economy and running performance are presently unknown. Further research is clearly required to investigate the relative efficacy of different forms of running in sand as a possible strategy to improve running economy and performance.

3.4 Resistance Training

3.4.1 Heavy and Strength-Endurance Training

Understandably, running training makes up a significant proportion of a runners training. However, other forms of training are undertaken to bring about specific physiological adaptations that could directly or indirectly (i.e. reduce injury risk) improve performance. A common training method often utilized by distance runners is resistance training. Various forms of resistance training can be adopted and several have been shown to improve running economy in recreational (Hickson et al., 1988; Taipale et al., 2009; Taipale, Mikkola, Vesterinen, et al., 2013), moderately trained (Albracht & Arampatzis, 2013; Barnes, Hopkins, McGuigan, Northuis, & Kilding, in press; Berryman et al., 2010; Francesca et al., 2012; Guglielmo et al., 2009; Johnston et al., 1997; Storen et al., 2008), and highly trained runners (Millet et al., 2002; Sedano et al., 2013) (Table 4). To date, resistance-training interventions have been designed specifically to increase muscular strength, power, muscular endurance, and/or promote neural adaptations. For the purposes of this review, and in keeping with use of resistance methods in the literature (Table 4) the term ‘resistance training’ will refer to any training that uses a resistance to the force of muscular contraction at a low velocity, while ‘heavy resistance training’ will refer to those studies that utilize loads <6RM (1-6 RM) and ‘strength-endurance resistance training’ will refer to studies utilizing loads ≥6 RM (7+ RM).

Table 4: Comparison of effects on running economy and performance following adaptation to various resistance training, plyometric and explosive resistance training interventions.

Study (year)	Subjects	Volume	Frequency and duration	Control	Results (%)	
					Running economy	Performance (distance)
Resistance training						
Johnston et al. (1997) (Johnston et al., 1997)	12 moderately trained female runners	2-3 sets of 6-20 RM in addition to endurance training	3 d/wk for 10 wk	Endurance running	↑ 4	n/a
Millet et al. (2002) (Millet et al., 2002)	15 highly trained male triathletes	3-5 sets of 3-5 RM in addition to endurance training	2 d/wk for 14 wk	Endurance training (swim, cycle, run)	↑ 5.6-7	↑ 2.6 (3-km)
Storen et al.	17 moderately	4 sets of 4 RM in	8 wk	Endurance	↑ 5	↑ 21.3 (time

(2008) (Støren et al., 2008)	trained male/female runners	addition to endurance training		running		to exhaustion at MAS)
Guglielmo et al. (2009) (Guglielmo et al., 2009)	7 moderately trained runners	3-5 sets of 6 RM in addition to endurance training	2 d/wk for 4 wk	No control	↑ 6.2	n/a
Taipale et al. (2009) (Taipale et al., 2009)	18 recreational male runners	2-3 sets of 4-15 RM in addition to endurance training	2 d/wk for 8 wk	Circuit + endurance running	↑ 8	↑ 10
Ferrauti et al. (2010) (Ferrauti et al., 2010)	22 recreational male/female runners	4 sets of 3-5 RM or 3 sets of 20-25 RM in addition to endurance training	2 d/wk for 8 wk	Endurance training	↔	n/a
Mikkola et al. (2011) (Mikkola et al., 2011)	11 moderately trained male runners	3 sets of 4-6 RM in addition to endurance training	2 d/wk for 8 wk	No control	↔	n/a
Mikkola et al. (2011) (Mikkola et al., 2011)	6 moderately trained male runners	3 sets of 40-50 reps in addition to endurance training	2 d/wk for 8 wk	No control	↔	n/a
Berryman et al. (2010) (Berryman et al., 2010)	17 moderately trained male runners	3-6 sets of 8 reps in addition to endurance training	1 d/wk for 8 wk	Endurance running	↑ 4	↑ 4.3 (3-km)
Cheng et al. (2012) (Cheng et al., 2012)	24 recreational male runners	10 sets of 60 s whole body vibration semi squats	3 d/wk for 8 wk	Placebo resistance training + endurance training	↑ 7.8	n/a
Francesca et al. (2012) (Francesca et al., 2012)	16 moderately trained male runners	4 sets of 3-4 at 85-90% 1RM in addition to endurance training	2 d/wk for 6 wk	Endurance training	↑ 6.2	n/a
Francesca et al. (2012) (Francesca et al., 2012)	16 moderately trained male runners	3 sets of 10 reps at 70% 1RM in addition to endurance training	2 d/wk for 6 wk	Endurance training	↔	n/a
Albracht and Arampatzis (2013) (Albracht & Arampatzis, 2013)	26 recreational male runners	5 sets of 4 reps in addition to endurance training	4 d/wk for 14 wk	Endurance running	↑ 4	n/a
Sedano et al. (2013) (Sedano et al., 2013)	12 highly trained male runners	3 sets of 7-10 reps in addition to endurance training	2 d/wk for 12 wk	Circuit + endurance running	↑ 5	↑ 1.2 (3-km)
Sedano et al. (2013) (Sedano et al., 2013)	12 highly trained male runners	3 sets of 20 reps in addition to endurance training	2 d/wk for 12 wk	Circuit + endurance running	↑ 1.6	↔ (3-km)
Taipale et al. (2013) (Taipale, Mikkola, Vesterinen, et al., 2013)	18 recreational male runners	2-3 sets of 4-6 reps in addition to endurance training	1-2 d/wk for 8 wk	Endurance training	↔	n/a
Plyometric / Explosive resistance training						
Paavolainen et al. (1999) (Paavolainen, Hakkinen, et al., 1999)	22 moderately training male runners	15-90 min/session in addition to endurance training	9 wk	Endurance running and circuit training	↑ 24.4-33.8	↑ 3.1 (5-km)
Spurrs et al. (2003) (Spurrs et al., 2003)	17 moderately trained male	2-3 sets of 8-15 reps in addition to	2-3 d/wk for 6 wk	Endurance running	↑ 5.7	↑ 2.7 (3-km)

al., 2003)	runners	endurance training					
Turner et al. (2003) (Turner et al., 2003)	18 recreational male/female runners	1 set of 5-25 reps in addition to endurance training	3 d/wk for 6 wk	Endurance running	↑ 2-3	n/a	
Saunders et al. (2006) (Saunders et al., 2006)	15 highly trained male runners	30 min/session in addition to endurance training	3 d/wk for 9 wk	Endurance running	↑ 4	n/a	
Mikkola et al. (2007) (Mikkola, Rusko, Nummela, Pollari, et al., 2007)	25 moderately trained male/female runners	30-60 min session in addition to endurance training	3 d/wk for 8 wk	Endurance running	↑ 3	↔ (peak running speed)	
Guglielmo et al. (2009) (Guglielmo et al., 2009)	9 moderately trained runners	3-5 sets of 12 RM in addition to endurance training	2 d/wk for 4 wk	No control	↑ 1.9	n/a	
Taipale et al. (2009) (Taipale et al., 2009)	17 recreational male runners	2-3 sets of 5-10 reps in addition to endurance training	2 d/wk for 8 wk	Circuit + endurance running	↑ 4	↑ 6	
Berryman et al. (2010) (Berryman et al., 2010)	16 moderately trained male runners	3-6 sets of 8 reps in addition to endurance training	1 d/wk for 8 wk	Endurance running	↑ 7	↑ 5.1 (3-km)	
Mikkola et al. (2011) (Mikkola et al., 2011)	10 moderately trained male runners	3 sets of 6 reps in addition to endurance training	2 d/wk for 8 wk	No control	↔	n/a	
Taipale et al. (2013) (Taipale, Mikkola, Vesterinen, et al., 2013)	17 recreational male runners	2-3 sets of 5-10 reps in addition to endurance training	1-2 d/wk for 8 wk	Endurance training	↔	n/a	
Taipale et al. (2013) (Taipale, Mikkola, Vesterinen, et al., 2013)	16 recreational male runners	2-3 sets of 4-10 reps in addition to endurance training	1-2 d/wk for 8 wk	Endurance training	↔	n/a	

Highly trained = national/international level and $VO_{2max} > 65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; **moderately trained** = weekly running volume $> 30 \text{ km}\cdot\text{wk}^{-1}$; **recreational** = weekly running volume $< 30 \text{ km}\cdot\text{wk}^{-1}$; **reps** = repetitions; **RM** = repetition maximum; **↑** indicates increase; **↔** indicates no change; **↓** indicates decrease; **n/a** indicates not measured.

3.4.1.1 Mechanisms of Improvement following Heavy or Strength-Endurance Resistance Training

Resistance training may improve running economy through several mechanisms. Kyrolainen et al. (2001) proposed that resistance training may improve running economy through improved lower limb coordination and co-activation of muscles (Kyrolainen et al., 2001), thereby increasing leg stiffness and decreasing stance phase contact times, allowing a faster transition from the braking to the propulsive phase through elastic recoil (Cheng et al., 2012; Kyrolainen et al., 2001; Paavolainen, Hakkinen, et al., 1999; Paavolainen, Nummela, Rusko, et al., 1999; Paavolainen, Nummela, & Rusko, 1999; Sale, 1988). An increase in strength following heavy resistance training as a result of increased motor unit recruitment and motor unit

synchronization may improve mechanical efficiency and motor recruitment patterns (Kraemer et al., 1996; Sale, 1988). Greater muscular strength following heavy or strength-endurance resistance training has previously been shown to have a fatigue resistant effect, resulting in a smaller increase in running economy during sustained endurance exercise (Hayes, French, & Thomas, 2011). Storen et al. (2008) suggested that the main training response to 8 weeks of heavy resistance training in 17 male and female distance runners was a change in muscle recruitment patterns, yet no direct measurement of muscle recruitment (i.e. EMG) was provided to support this notion (Storen et al., 2008). The authors did report a 33% increase in strength in addition to a 5% improvement in running economy (Storen et al., 2008). Several other studies (Guglielmo et al., 2009; Millet et al., 2002; Storen et al., 2008; Taipale et al., 2009) have reported concomitant improvements in running economy and maximal strength following heavy resistance training, indicating positive neuromuscular adaptations occurred.

Other studies (Berryman et al., 2010; Cheng et al., 2012; Francesca et al., 2012; Mikkola et al., 2011; Sedano et al., 2013) however, demonstrate convincing evidence that the combination of strength-endurance resistance training and endurance training improves running performance and enhances running economy in moderate or highly trained runners (Table 4). Heavy resistance training may primarily cause hypertrophy of type IIA and IIB (fast twitch) fibers, but also type I (slow twitch) fibers (Staron et al., 1994; Staron et al., 1991), resulting in less motor unit activation to produce a given force (Moritani & deVries, 1979). Unfortunately, increases in body mass are an undesirable side effect to increases in muscle strength from resistance training that could be counter-productive to distance running performance. However, increased muscular strength might primarily come from neural adaptations without observable muscle hypertrophy (Hakkinen, 1994) since most studies reported little or no changes in body mass, fat free mass, percent body fat or girth measurements following heavy resistance training. Sale (1998) states that heavy resistance training induces changes in the nervous system which allow an athlete to increase the activation of the working muscles, thus producing a greater net force with each stride (Sale, 1988). It is well documented that initial performance gains following heavy resistance training are a result of neuromuscular adaptations rather than within muscle adaptations (e.g. hypertrophy) (Kraemer et al., 1996; Sale, 1988). Regardless of whether strength gains occur at the muscular level, neural level, or both, if a more efficient recruitment pattern is induced, decreases in oxygen consumption at a given speed are likely to occur (Bransford & Howley, 1977; Patton & Vogel, 1977).

Improved running economy may also be due to increases in strength that causes positive changes in mechanical aspects of running style (i.e. improved biomechanical efficiency) (Johnston et al., 1997), thus allowing a runner to do less work at a given running speed. A number of biomechanical variables have been identified that relate to running economy (see Part I), thereby providing support for the hypothesis that mechanical aspects of running style have an influence on running economy (Anderson, 1996). Another possible explanation for improved running economy following heavy resistance training could involve muscle fiber-type conversion, though existing data in athletes are conflicting (Coyle, Martin, Bloomfield, Lowry, & Holloszy, 1985; Staron et al., 1994; Staron et al., 1991; Staron et al., 1990). For example, Staron et al. (1990, 1991, 1994) found a decrease in the percent of fast glycolytic type IIX fibers, with a simultaneous increase in the percent of fast oxidative glycolytic type IIA fibers, following a heavy-resistance low-velocity lower body resistance training program in untrained men (Staron et al., 1994) and women (Staron et al., 1994; Staron et al., 1991; Staron et al., 1990). Conversely, Coyle et al. (1985) reported that VO_2 remained unchanged for the same absolute submaximal intensity throughout the detraining period, despite a large shift from type IIA to IIX fibers when studying 7 endurance-trained subjects 12, 21, 56, and 84 days after cessation of training suggesting that muscle fiber conversion has little or no impact on running economy (Coyle et al., 1985).

3.4.1.2 Heavy versus Strength-Endurance Resistance Training

Several studies have attempted to determine which form of concurrent endurance and resistance training might be the most effective at improving running performance in highly trained runners. Sedano et al. (2013) prescribed 18 well-trained male runners with 12 weeks of either heavy resistance training or strength-endurance resistance training in addition to their normal running training (Sedano et al., 2013). The heavy-resistance group elicited substantially greater improvements in running economy (5% vs 1.6%) and 3-km run performance (1.2% vs. no change) compared to the strength-endurance resistance training group (Sedano et al., 2013). Similarly, Berryman et al. (2010) found that 8 weeks of strength-endurance resistance training (purely concentric semi-squats on a guided squat rack allowing only vertical movements) improved running economy by 4% in 17 moderately trained male runners (Berryman et al., 2010). The improvement in economy, along with a substantial increase in peak power, resulted in a 4.3% improvement in 3-km running time, without an increase in VO_{2max} , with gains attributed to changes in neuromuscular characteristics (Berryman et al., 2010). Taipale et al. (2009) also reported significant improvements in running economy (8%) and velocity at VO_{2max} (vVO_{2max}) (10%) along with improvements in neuromuscular performance (1RM maximal strength and

EMG vastus lateralis activity) after 8 weeks of heavy resistance training in recreation runners (Taipale et al., 2009). However, heavy resistance training was performed in addition to a significant increase in endurance training volume, therefore the improvements in running economy may be related to the increased volume of training rather than the resistance training itself since the subjects in this study were recreational runners (Taipale et al., 2009). The only study (Johnston et al., 1997) to examine any form of resistance training in females found that in 10 weeks of strength-endurance resistance training combined with endurance training significantly improved running economy (4%) without any changes in $VO_2\text{max}$.

The available data involving athletes suggests running economy can be improved with simultaneous resistance and endurance training, with no chronic deleterious effect to $VO_2\text{max}$ or running performance (Saunders, Pyne, et al., 2004a). Examination of the acute effects of resistance and endurance training sequence on running economy show that running performance is impaired to a greater degree the day following the resistance train then run sequence compared with the run then resistance train sequence (Doma & Deakin, 2013). The combination of improved biomechanical efficiency along with greater motor unit recruitment and muscle coordination may allow for a reduction in relative workload (Hoff, Helgerud, & Wisloff, 1999). Additionally, the improved running mechanics and neuromuscular efficiency may result in a decrease in oxygen consumption, thereby improving running economy. Most of the studies discussed here showed improvements in running economy in 10 weeks or less, however more studies are needed to determine if improvements can be made in shorter periods or what the time course of changes in running economy are. Most studies demonstrating improvement in running economy following resistance training cite enhancements in neuromuscular characteristics as the mechanism for improvement, however most studies only make indirect measures of neuromuscular activity. Therefore more direct measures such as EMG analysis may allow researchers to identify if a transfer of learning from resistance training to running performance occurs. Additionally, each of these studies employed different modes of resistance training; therefore more research is required to determine which mode of resistance training might be most effective at improving running economy and performance in well-trained athletes.

3.4.2 Plyometric and Explosive Resistance Training

The concept of movement specificity suggests that the type of resistance training used by runners should closely simulate the movement that will be performed during training and competition (Jung, 2003). Plyometrics or explosive resistance training is a

specific form of strength training that aims to enhance the ability of muscles to generate power by exaggerating the SSC, using explosive exercises such as jumping, hopping and bounding (Turner et al., 2003).

3.4.2.1 Mechanisms of Improvement Following Plyometric or Explosive Resistance Training

Plyometric training has the potential to increase the stiffness of the muscle-tendon system, which allows the body to store and utilize elastic energy more efficiently, resulting in decreased ground contact time and reduced energy expenditure (Anderson, 1996; Cavagna et al., 1964; Cavanagh & Kram, 1985b; Hakkinen et al., 1985; Spurrs et al., 2003). Paavolainen et al. (1999) indicated that 9 weeks of explosive resistance training improved 5-km run performance (3.1%) and running economy (8.1%) with no changes in VO_2max in 22 moderately trained male runners (Paavolainen, Hakkinen, et al., 1999). Furthermore, significant improvements in velocity over a 20-m sprint (3.4%), distance jumped (4.6%), along with a concurrent decrease in stance phase contact times were observed (Paavolainen, Hakkinen, et al., 1999). These variables are thought to represent indirect measures of the neuromuscular system's ability to repeatedly produce rapid force during intense exercise, and the capability to store and utilize elastic energy (Paavolainen, Hakkinen, et al., 1999; Paavolainen, Nummela, Rusko, et al., 1999; Paavolainen, Nummela, & Rusko, 1999). The authors suggested that the improved performance was a result of enhanced neuromuscular characteristics and biomechanical efficiency that were transferred into improved muscle power and running economy (Paavolainen, Hakkinen, et al., 1999).

The importance of the neuromuscular characteristics in determining running economy and thereby running performance has also been pointed out by Dalleau et al. (Dalleau et al., 1998). They showed that the energy demand during running is significantly related to the stiffness of the propulsive leg, which was also demonstrated by Spurrs et al. (Spurrs et al., 2003). They showed six weeks of plyometric training significantly improved running economy, muscle-tendon stiffness, maximal isometric force, rate of force development, jump height, five jump distance and 3-km time trial performance. Plyometric training consisted of two to three session per week of various unloaded jumps, bounds, and hops. Several other studies (Table 4) have provided support that simultaneous plyometric or explosive resistance training and endurance training improves running economy in recreational (Taipale et al., 2009; Taipale, Mikkola, Vesterinen, et al., 2013; Turner et al., 2003), moderately trained (Barnes, Hopkins, et al., in press; Berryman et al., 2010; Guglielmo et al., 2009; Hamilton et al.,

2006; Mikkola, Rusko, Nummela, Pollari, et al., 2007; Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003), and highly trained runners (Saunders et al., 2006). Saunders et al. (2006) examined the effects of 9 weeks of plyometric training on running economy in highly trained runners using loaded and unloaded exercises three times per week (Saunders et al., 2006). The subjects were tested for running economy at 14, 16, and 18 km·h⁻¹ at weeks 5 and 9, however, significant improvements were only found at week 9 for the 18 km·h⁻¹ test. Other studies have shown improvements in running economy after 8 weeks of plyometric training in moderately trained runners with no change in VO₂max (Berryman et al., 2010; Mikkola, Rusko, Nummela, Pollari, et al., 2007), with the former study showing a 7% improvement in running economy and 5.1% in 3-km run performance. Proposed explanations for the improvements include increased lower limb stiffness and elastic energy return, enhanced muscle strength and power or alternatively enhance running mechanics. Turner et al. (2003), however, reported no change in four indirect measures of the ability of the muscles to store and return elastic energy despite a 3% improvement in running economy following 6 weeks of plyometric training in recreational runners (Turner et al., 2003) suggesting that either more direct measures of potential mechanisms that could improve running economy need to be made in future research or other factors have yet to be elucidated as potential mechanisms for enhancing running economy following plyometric training.

3.4.2.2. Lessons from Cross-Country Skiers

It has also been suggested that increases in muscle force and rate of force development, rather than increased maximal strength might be the mechanisms which alter neuromuscular and perhaps biomechanical efficiency. This is in line with Mikkola et al. (2007) showing significant improvements in sport-specific rapid force production (maximal speed over 30 meters) and activation of the leg extensors following 8 weeks of concurrent endurance and explosive movement-specific strength training in 19 moderately trained male cross-country skiers (Mikkola, Rusko, Nummela, Paavolainen, & Hakkinen, 2007). It was also reported that the sport-specific work economy improved by 7%, which is in line with previous studies (Hoff, Gran, & Helgerud, 2002; Hoff et al., 1999; Osteras, Helgerud, & Hoff, 2002) that reported improvements in economy after concurrent endurance and sport-specific resistance training that mimicked the double poling action used in cross country skiing.

It has been proposed that more efficient motor recruitment patterns as a result of training, whether at the neural or muscular level, may decrease the oxygen demand at a given submaximal work rate (Johnston et al., 1997). The increased maximal force of trained muscles might affect the recruitment of muscles so that athletes are able to use

relatively more type I motor units, leading to more economical endurance performance (Hoff et al., 1999). Osteras et al. (2002) and Hoff et al. (1999) proposed that increased rate of force development and increased peak force due to explosive resistance training can give a longer recovery period between the muscle contractions, leading to better blood perfusion and thereby enhancing work economy in endurance-trained athletes (Hoff et al., 1999; Osteras et al., 2002). In support, the latter study (Hoff et al., 1999) reported a 22% improvement in work economy and improved time to exhaustion (9.1%), strength (14.5%) and peak force (27%) following 9 weeks of resisted double poling in which subjects performed 3 sets of 6 RM, 3 days per week without an increase in VO_2max . These improvements were reported due to decreases in relative workload (reduced percentage of maximal force) and time to peak force measured during the double poling action. Despite the different modes of testing, the weight bearing nature of the double-poling cross-country ski test could indicate these results may be applicable to running economy.

3.4.3 Resistance Training versus Plyometric or Explosive Resistance Training

The concept of movement specificity suggests that the type of resistance training used should closely model the movement that will be performed in competition (Jung, 2003). Consequently, Paavolainen et al. (1999) stated that explosive training, mimicking the eccentric phase of running, is most likely to improve the use of stored elastic energy and motor unit synchronization which increases the ability of the lower-limb joints to act stiffer on ground contact (Paavolainen, Hakkinen, et al., 1999). Moreover, Millet et al. (2002) stated that explosive-strength training leads to different muscular adaptations than does typical heavy weight training (Millet et al., 2002); for example, a greater increase in the rate of activation of the motor units. The available data (Table 4), however, suggests that of the studies (Barnes, Hopkins, et al., in press; Berryman et al., 2010; Guglielmo et al., 2009; Taipale et al., 2009; Taipale, Mikkola, Vesterinen, et al., 2013) that included a resistance training and plyometric or explosive resistance training group, three of the five studies (Barnes, Hopkins, et al., in press; Guglielmo et al., 2009; Taipale et al., 2009; Taipale, Mikkola, Vesterinen, et al., 2013) demonstrated greater improvements in running economy following traditional resistance training, while one (Taipale, Mikkola, Vesterinen, et al., 2013) showed no changes in economy in either type of training.

According to Guglielmo et al. (2009) when comparing heavy resistance training to explosive resistance training performed on the same equipment, heavy weight training seems to be more efficient for the improvement of running economy (Guglielmo

et al., 2009). Paton and Hopkins (2004) came to the same conclusion when reviewing the effects of high-intensity training on performance and physiology in endurance athletes (Paton & Hopkins, 2004). Similarly, when comparing various modes of traditional resistance training, Sedano et al. (2013) found that a low-repetition high-resistance program was superior to a high-repetition low-resistance program at improving running economy (Sedano et al., 2013). This is assuming that each of these studies resistance training programs were matched for volume load and the subjects in each group were matched for training history and ability level. It is reasonable to assume that there are individual responses to various modes of resistance training. However, until more data is collected to describe subject or training characteristics that may identify responders and non-responders to these different modes of resistance training the current data suggest that traditional resistance training may be superior to plyometric training, but any type of resistance may have a positive effect on running economy (Jung, 2003).

While the exact mechanisms responsible for the improved running economy following plyometric or explosive resistance training are unclear, the findings to date indicate that improved neuromuscular function likely plays a role in the enhancement in running economy and performance. However, this premise is based on indirect measures of neuromuscular function and elastic energy return such as contact times and vertical jump height. Enhancements in strength and power development during isolate tasks (e.g. vertical and forward jumps) may reflect neuromuscular adaptations but this has not been confirmed by more direct measurements of muscle recruitment, such as EMG activity. Thus is it not possible to infer that these adaptations translate into more efficient muscle recruitment patterns during running or that they are responsible for the enhanced running economy following plyometric training. Alternatively, changes in running style that result in more efficient gait patterns, kinematics and kinetics may also improve the economy of runners following plyometric or explosive resistance training. However, the majority of research into kinetics and kinematics of running has been descriptive and changes in biomechanical efficiency may be a result of improved neuromuscular efficiency. Finally, significant improvements in work economy found in cross-country skiers (Hoff et al., 2002; Hoff et al., 1999; Mikkola, Rusko, Nummela, Paavolainen, et al., 2007; Osteras et al., 2002) and cyclist (Bastiaans, van Diemen, Veneberg, & Jeukendrup, 2001; Paton, 2009) performing movement specific modes of resistance training may provide evidence that these forms of training may be most beneficial to improving running economy and performance; therefore future studies should examine running specific forms of resistance training such as hill running, hypergravity running or running through sand.

3.5 Environmental Strategies

Interventions to improve running economy besides endurance and resistance training are constantly sought after by athletes, coaches and sports scientists, however there is a paucity of data regarding environmental strategies. Training at altitude, in the heat or in the cold offer three potential strategies for improving economy. Despite altitude exposure being reasonably well-researched over the past few decades, there is still limited data in regards to improving running economy; while heat and cold exposure have yet to be examined. Therefore the following section discusses the feasibility of improving running economy via the increased physiologic stress from training in hypoxic environments, warm to hot conditions or cold conditions.

3.5.1 Altitude Exposure

Many athletes undertake some form of altitude training to gain small improvements in physiology and performance. Results from a recent meta-analysis indicate ~1-4% performance enhancements following various protocols using natural and artificial altitude exposure in highly and moderately trained athletes (Bonetti & Hopkins, 2009). Improvements in performance have been primarily attributed to increased hematological parameters leading to an increase in maximal aerobic capacity (Levine & Stray-Gundersen, 1997; Robertson, Saunders, Pyne, Aughey, et al., 2010; Saunders, Telford, Pyne, Gore, & Hahn, 2009; Stray-Gundersen, Chapman, & Levine, 2001), however hypoxia-induced enhancements in muscle buffering capacity (Gore et al., 2001) and running economy (Saunders, Telford, et al., 2004; Saunders, Telford, Pyne, Hahn, et al., 2009) have also been suggested.

3.5.1.1 Altitude vs. Sea-level Natives

Several descriptive, cross-sectional and intervention studies have been conducted highlighting differences in running economy between altitude natives and individuals residing at sea level with equivocal results. While reporting the physiological characteristics of Kenyan runners living and training at altitude and the Scandinavian runners at sea level, Saltin et al. (1995) found that Kenyan runners had 5-15% lower VO_2 at submaximal running speeds ranging from 10 to 16 $km \cdot h^{-1}$ and did not accumulate lactate during running until near peak training intensities (Saltin et al., 1995). Similarly, Weston et al. (1999) reported Kenyan runners had better economy and higher resistance to fatigue while running at the same percentage of VO_2max than Caucasian runners (Weston, Karamizrak, Smith, Noakes, & Myburgh, 1999). It was reported that Kenyan runners who live and train at altitude have higher oxidative enzyme activities than their Caucasian counterparts of a similar VO_2max (Weston et al., 1999), which could be the reason for the improved running economy.

Data examining 46 weeks of training at 2210 m altitude in sea level and altitude natives suggest that changes in physiological and performance parameters by former sea level residents may result in difference changes or require longer periods at altitude to result in similar changes compared to altitude natives (Brothers et al., 2010). Sea level natives had significantly poorer running economy (+6.6%), lower VO_2max (-5.9%), and slower 1.5 mile run time (+5.4%) compared to altitude natives following similar training at altitude. Similarly, Lundby et al. (2007) reported that there were no significant changes in running economy of sea level natives after 8 weeks of exposure to 4100 m compared to altitude natives who had a 15% lower submaximal VO_2 than sea-level residents (Lundby et al., 2007), consistent with the observations of others (Hochachka et al., 1991; Marconi, Marzorati, Sciuto, Ferri, & Cerretelli, 2005; Saltin et al., 1995; Weston et al., 1999; Weston, Mbambo, & Myburgh, 2000).

3.5.1.2 Adaptation to Different Hypoxic Environments

In sea-level natives, several studies (Bailey et al., 1998; Burtcher et al., 2010; Katayama et al., 2003; Katayama et al., 2004; Levine & Stray-Gundersen, 1997; Neya et al., 2007; Richalet & Gore, 2008; Saunders, Telford, et al., 2004; Saunders, Telford, Pyne, Hahn, et al., 2009; Schmitt et al., 2006) have demonstrated improvements (2-7%) in running economy following different types, ascents and durations of altitude exposure (Table 5). Conversely, an equivocal number of studies have demonstrated that submaximal VO_2 at sea level remains largely unchanged following exposure to different hypoxic environments (Table 5) (Julian et al., 2004; Lundby et al., 2007; Robertson, Saunders, Pyne, Aughey, et al., 2010; Robertson, Saunders, Pyne, Gore, & Anson, 2010; Stray-Gundersen et al., 2001; Telford, Graham, & Sutton, 1996; Truijens et al., 2008).

Table 5: Comparison of effects on running economy and performance following adaptation to hypoxia experienced in studies with various protocols of natural and artificial altitude.

Study (year)	Subjects	Altitude type	Intervention	Control	Results (%)	
					Running economy	Performance (distance)
Telford et al. (1996) (Telford et al., 1996)	18 highly trained male runners	Natural altitude, LHTH	4 wk at 1700-2000 m, 24 h/day	LLTL	↔	↑ 2 (3.2-km)
Levine et al. (1997) (Levine & Stray-Gundersen, 1997)	26 moderately trained male/female runners	Natural altitude, LHTL	4 wk at 2500 m, 16-20 h/day	LLTL	↑ 4.8	↑ 1.4 (5-km)
Levine et al. (1997) (Levine & Stray-Gundersen, 1997)	26 moderately trained male/female runners	Natural altitude, LHTH	4 wk at 2500 m, 24 h/day	LLTL	↑ 2.8	↔ (5-km)
Bailey et al. (1998) (Bailey et al., 1998)	23 moderately trained male/female runners	Natural altitude, LHTH	4 wk at 1500-2000 m, 24 h/day	LLTL	↔	n/a
Stray-Gundersen et al. (2001) (Stray-Gundersen et al., 2001)	22 highly trained male/female runners	Natural altitude, LHTH	27 days at 2500 m, 24 h/day	No control	↔	↑ 1.1 (3-km)
Katayama et al. (2003) (Katayama et al., 2003)	12 highly trained male runners	Simulated altitude, LHTL	3 days/wk for 3 wk at 4500 m, 90 min/day	LLTL	↑ 3.3	↑ 1 (3-km)
Julian et al. (2004) (Julian et al., 2004)	14 highly trained male/female runners	Simulated altitude, LHTL	5 days/wk for 4 wk at 3600-5000 m,	LLTL	↔	↔ (3-km)
Katayama et al. (2004) (Katayama et al., 2004)	15 highly trained male runners	Simulated altitude, LHTL	14 days at 4500 m, 3 h/day	LLTL	↑ 2.9	↑ 1.3 (3-km)
Saunders et al. (2004) (Saunders, Telford, et al., 2004)	10 highly trained male runners	Artificial altitude, LHTL	5 days/wk for 4 wk at 2000-3100 m, 9-12 h/day	LLTL	↑ 3.3	n/a
Saunders et al. (2004) (Saunders, Telford, et al., 2004)	10 highly trained male runners	Natural altitude, LHTL	5 days/wk for 4 wk at 2000-3100 m, 9-12 h/day	LLTL	↔	n/a
Schmitt et al. (2006) (Schmitt et al., 2006)	11 moderately trained male runners	Natural altitude, LHTL	17-24 days at 2500-3500 m, 11-14 h/day	LLTL	↑ 7.0	n/a
Lundby et al. (2007) (Lundby et al., 2007)	24 highly trained male/female runners	Natural altitude, LHTH	4 wk at 2500-2850 m, 24 h/day	No control	↔	n/a
Neya et al. (2007) (Neya et al., 2007)	16 highly trained male runners	Artificial altitude, LHTL	29 days at 3000 m, 11 h/day	LLTL	↑ 5.5	n/a
Neya et al. (2007) (Neya et al., 2007)	15 highly trained male runners	Artificial altitude, LHTH	29 days at 3000 m, 11 h/day	LLTL	↔	n/a
Truijens et al. (2008) (Truijens et al., 2008)	10 moderately trained male/female runners	Artificial altitude, LHTL	5 days/wk for 4000-5500 m, 3 h/day	LLTL	↔	n/a
Saunders et al. (2009) (Saunders, Telford, Pyne, Hahn, et al., 2009)	18 highly trained runners	Artificial altitude, LHTL	46 days at 2860, 9 h/day	LLTL	↑ 3.2	↑ 1.9 (1500-m)
Burtscher et al.	11 moderately	Artificial	3 day/wh for 2 x	LLTL	↑ 2.3	↑ 31 (time to

(2010) (Burtscher et al., 2010)	trained male/female runners	altitude, LHTL	5 wk at 3200-5500 m, 2 h/day				exhaustion at MAS)
Robertson et al. (2010) (Robertson, Saunders, Pyne, Gore, et al., 2010)	8 highly trained male/female runners	Artificial altitude, LHTL+TH	3 wk at 3000 m, 14 h/day + 4 day/wk training at 2200 m	No control	↔		↑ 1.1 (3-km)
Robertson et al. (2010) (Robertson, Saunders, Pyne, Gore, et al., 2010)	9 highly trained male/female runners	Artificial altitude, LLTH	4 day/wk for 3 wk training at 2200 m	No control	↔		↔ (3-km)
Robertson et al. (2010) (Robertson, Saunders, Pyne, Gore, et al., 2010)	16 highly trained male/female runners	Artificial altitude, LHTL	3 wk training at 3000 m, 14 h/day	LLTL	↔		↑ 1.9 (3-km)

Highly trained = national/international level and $VO_{2max} > 65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; **moderately trained** = weekly running volume $> 30 \text{ km}\cdot\text{wk}^{-1}$; **recreational** = weekly running volume $< 30 \text{ km}\cdot\text{wk}^{-1}$; **LTH** = live high train high; **LLTL** = live low train low; **LHTL** = live high train low; low altitude = $< 1000 \text{ m}$, high altitude = $> 1500 \text{ m}$ (Bonetti & Hopkins, 2009); ↑ indicates increase; ↔ indicates no change; ↓ indicates decrease; n/a indicates not measured;

3.5.1.2.1 Blood Parameters

Mechanisms that have been suggested to explain the discrepancy in improvements in economy after altitude exposure have been related to differences in changes in hemoglobin mass and concentration, following hypoxic exposure. While the dosing of hypoxia for the enhancement of the total hemoglobin mass currently is well defined this does not apply to running economy. About 400 hours of hypoxia corresponding to an altitude $> 2100 \text{ m}$ seem to be necessary to increase total hemoglobin mass (Saunders, Telford, Pyne, Hahn, et al., 2009). In a study by Burtscher et al. (2010), the duration of hypoxic exposure was only 30 h during one 5 week period which unsurprisingly was insufficient to significantly increase total hemoglobin mass, but was adequate to elicit an improvement (2.3%) in running economy (Burtscher et al., 2010). The authors did report small increases in hemoglobin concentration and hematocrit, which were closely related to the improvement in running economy. An increase in hematocrit results in a linear increase of the oxygen carrying capacity and an exponential increase in blood viscosity (Burtscher et al., 2010). Because blood viscosity is not highly dependent on hematocrit at high cardiac outputs (Burtscher et al., 2010) the enhanced oxygen carrying capacity could contribute to the improved running economy and performance after hypoxia. Levine et al. (1997) reported that moderately trained runners living at moderate altitude (2500 m) and training at low altitude (1250 m) increased red cell mass (9%) as well as improved VO_{2max} (5%) and running economy (2-5%) after return to sea level (Levine & Stray-Gundersen, 1997). The authors suggested the enhanced hematological properties and oxygen-carrying capacity of the blood improvements translated into improved 5-km time-trial performance.

3.5.1.2.2 Cardiorespiratory Adaptations

The findings from a number of studies suggests that enhancements in running economy following hypoxic exposure may be the result of decreased cardiorespiratory costs (decreased V_E , lower HR) (Green et al., 2000; Katayama et al., 2004; Saunders, Telford, Pyne, Hahn, et al., 2009), a shift toward a greater glycolytic involvement in ATP regeneration (Green et al., 2000), greater carbohydrate utilization during oxidative phosphorylation (Gore et al., 2001; Roberts et al., 1996), increased ability of the excitation and contraction processes to perform work at lower energy costs (Gore, Clark, & Saunders, 2007; Green et al., 2000), and/or acclimatization-induced transformation of muscle fiber types (Green et al., 2000). One study examining the effects of ~46 nights at 2860 m simulated altitude on running economy and performance prior to the competitive track season found altitude improved running economy by 1.0-5.2%, increased hemoglobin mass by 4.9%, and decreased submaximal heart rate by 3.1% (Saunders, Telford, Pyne, Hahn, et al., 2009). The authors suggest plausible mechanisms for improved running economy include an increase in ATP production per mole of O_2 used, a decrease in the ATP cost of muscle contraction, and a decrease in the cardiorespiratory cost of O_2 transport. Another recent study demonstrated that 11 to 14 hours a day for 17-24 days of normobaric hypoxia (2500-3500 m) improved running economy by 7% (Schmitt et al., 2006). The authors suggested that changes in substrate utilization and lower cardiorespiratory costs contributed to the improved running economy, which is supported by the increased submaximal RER and the decreased minute ventilation and heart rate values within the experimental groups. More recently, it was demonstrated that 3 hours per day for 2 weeks of intermittent exposure to normobaric hypoxia (equivalent of 4500 m) improved running economy by 2.6% ($14 \text{ km}\cdot\text{h}^{-1}$) and 2.9% ($16 \text{ km}\cdot\text{h}^{-1}$). The improved running economy was accompanied by a decreased HR (3.3% and 3.9% at 14 and 16 $\text{km}\cdot\text{h}^{-1}$, respectively) and a trend towards improved 3000 m run time (1.3%) (Katayama et al., 2004).

3.5.1.2.3 Substrate Metabolism

The findings from other studies indicate that a small shift in substrate metabolism towards increase in carbohydrate use and lower cardiorespiratory costs, such as decreased minute ventilation and heart rate contributed to the improved running economy after a period of altitude exposure (Burtscher et al., 2010; Schmitt et al., 2006). Both studies reported an improvement in running economy (2.3% (Burtscher et al., 2010) and 7.7% (Schmitt et al., 2006)) with an accompanying shift towards carbohydrate metabolism. The former study, reported that two 5-week periods of intermittent hypoxia (3200-5500 m) 3 days per week for 2 hours each day improved

running economy only during the first 5-week period of intermittent hypoxia when compared to training alone. Although running economy continuously improved during the 13-week study period, no further differences changes occurred after the first 5-week period. These findings suggest that mainly intermittent hypoxia must have been responsible for the improvement in running economy during the first 5 weeks and running training during the following 8 weeks. These results emphasizes the importance of the training phase on the effectiveness of altitude exposure on running economy.

3.5.1.2.4 Metabolic Efficiency

Results from other studies (Gore et al., 2007; Saunders, Telford, et al., 2004) suggest the physiological mechanisms eliciting an improved running economy in highly trained runners after hypoxic exposure appear unrelated to decreased ventilation or a substantial shift in substrate use. Therefore, it is possible that the main mechanisms responsible for improved running economy at sea level after a period of altitude exposure are either an increase in the ATP production per mole of oxygen used and/or a decrease in the ATP cost of muscle contraction. Katayama et al. (2003, 2007) have demonstrated on several occasions that intermittent hypoxic exposure improves running economy in highly trained runners without changes in ventilation or substrate use (Katayama et al., 2003; Katayama et al., 2007). The first study reported that simulated hypoxic exposure using intermittent hypobaria of 4500 m 3 hours per day for 14 consecutive days improved running economy by 2.6% ($14 \text{ km}\cdot\text{h}^{-1}$) and 3.3% ($16 \text{ km}\cdot\text{h}^{-1}$), improved 3000 m run time by 1% and time to exhaustion on the treadmill by 2.7% (Katayama et al., 2003). Another recent study demonstrated that 20 days of live high (simulated altitude 2000-3100 m) train low improved running economy (3.3%, $p = 0.005$) in the absence of any changes in V_E , RER, HR or hemoglobin mass (Saunders, Telford, et al., 2004). There was also no evidence of an increase in lactate concentration after the live high train low intervention, suggesting that the lower aerobic demand of running was not attributable to an increased anaerobic energy contribution.

Hochachka (1988) was the first to describe the processes that ameliorate energetic efficiency following hypoxic exposure (Hochachka, 1988), and more recently by Gore et al. (2007) (Gore et al., 2007). The high ATP use required for endurance exercise can only be supported by mitochondrial oxidative phosphorylation, and, consequently, mitochondrial efficiency has a direct influence on whole-body efficiency (Ponsot et al., 2006). At the cellular level mitochondrial efficiency is defined by the coupling between ATP formation and substrate oxidation; either an increase in ATP per mol of oxygen used or decrease in the amount of substrate to support ATP demand

improves metabolic efficiency and theoretically running economy. Neya et al. (2007) suggested that it is possible that hypoxic exposure resulted in tighter coupling of muscular intracellular bioenergetics, which improved mitochondrial efficiency and subsequently running economy (Neya et al., 2007). A reduced energy requirement of one or more processes involved in excitation and contraction of the working muscles has been previously postulated by Green et al. (2000), possibly as a result of a reduction in by-product accumulation, such as ADP, inorganic phosphate and H^+ , that occurs after altitude acclimatization, which increases the amount of free energy released from ATP hydrolysis and depresses the need to maintain hydrolysis rates at pre-acclimatized levels (Green et al., 2000).

3.5.1.2.5 Muscle Fiber Type

It has been shown that the type I muscle fibers are considerably more efficient than type II muscle fibers (see section on *Muscle Fiber Type* – Part I). Acclimatization-induced transformation of fiber types could conceivably underlie changes in neuromuscular efficiency; however, this has yet to be studied runners.

In summary, the literature indicates that altitude exposure for runners has no detrimental effects on running economy and that there is good evidence to suggest that it may lead to worthwhile improvements in running economy at sea-level. Altitude acclimatization results in both central and peripheral adaptations that improve oxygen delivery and utilization and enhance metabolic efficiency, mechanisms that potentially could improve an athletes running economy. Many of the studies that did not find improved running economy (Table 5) after altitude exposure were performed close to the competition season emphasizing the importance of training phase on the effectiveness of altitude exposure on running economy. However, it cannot be excluded that more severe hypoxia and longer durations of exposure would affect running economy even close to competition season.

3.5.2 Heat

Adaptations associated with acute and chronic training bouts in warm to hot conditions may attenuate the magnitude of the thermoregulatory response (increase V_E , sweating and circulation) and reduce the energy requirements (improved efficiency) associated with heat stress (Bailey & Pate, 1991; Svedenhag, 2000). The elevated C_{Temp} resulting from training in hyperthermic conditions may improve running economy by increasing the mechanical efficiency and/or metabolic efficiency in the working musculature (Maron et al., 1976; Morgan, Martin, et al., 1989; Rowell et al., 1969). It is also conceivable that running economy may improve with heat acclimatization due to

the corresponding increase in plasma volume. Plasma volume can increase by up to 12% following training in the heat (Bailey & Pate, 1991). The increase in plasma volume assists in the maintenance of stroke volume by preventing reductions in mean arterial pressure, central venous pressure, and cardiac filling (Laursen & Jenkins, 2002), which in turn reduces myocardial work (Bailey & Pate, 1991; Coyle, Hopper, & Coggan, 1990). While theoretically training in the heat should improve running economy, currently no data exists regarding the effectiveness of this training modality. However, the acute effects of temperature on running economy and stride parameters has shown that leg temperature manipulation did not influence running economy despite changes in stride parameters that might indicate restricted muscle-tendon elasticity after pre-cooling (Folland, Rowlands, Thorp, & Walmsley, 2006).

3.5.3 Cold

Several recent studies (Ito, Nakano, Yamane, Amano, & Matsumoto, 2013; Sandsund et al., 2012) have found that training in cold conditions induced similar metabolic responses to running in heat, which may enhance running economy. Ito et al. (2013) found in 7 male athletes running at 70% VO_2max for 30 min in a climate chamber at an ambient temperature of 5°C and in the presence of man-made rain (40 $\text{mm}\cdot\text{hr}^{-1}$ of precipitation), esophageal and mean skin temperature were significantly lower in rain than in control, presumably due to circulation forced away from the skin to warm and protect vital organs (Ito et al., 2013). Minute ventilation, HR, VO_2 and plasma lactate levels were also significantly higher in rain than in control (Ito et al., 2013).

Training in the heat or cold may also improve running economy and performance at normal temperatures, by allowing runners to compete at any given speed with a lower HR, C_{Temp} , and V_E , all factors associated with improved running economy (Thomas et al., 1995; Thomas et al., 1999). Therefore future research should examine plausibility of using heat and/or cold exposure as a strategy to improve running economy.

3.6 Stretching

There appears to be equivocal results in regards to the effects of stretching or flexibility on running economy. Some researchers have identified an inverse relationship between flexibility and running economy; that is, less flexibility is associated with greater running economy (lower VO_2) (Craib et al., 1996; Gleim et al., 1990; Hunter et al., 2011; Jones, 2002; Trehearn & Buresh, 2009). Gleim et al. (1990) tested 100 male and female subjects over a range of speeds from 3 to 12 $\text{km}\cdot\text{hr}^{-1}$ and

found that those who exhibited less flexibility in a battery of 11 trunk and lower limb flexibility tests were most economical (Gleim et al., 1990). These results and others suggest that the inflexibility of the lower limbs and trunk musculature as well as limited range of motion allow for greater elastic energy storage and use in the muscles and tendons during the running gait (Gleim et al., 1990; Jones, 2002). Specifically, it was suggested that inflexibility in the transverse and frontal planes of the trunk and hip regions of the body may stabilize the pelvis at the time of foot impact with the ground, reducing excessive range of motion and metabolically expensive stabilizing muscular activity (Gleim et al., 1990). Furthermore, research has demonstrated runners with tighter or stiffer musculotendinous structures demand less work from the exercising muscles (i.e. a lower VO_2) at any submaximal running velocity because they use more stored elastic energy while running (Craib et al., 1996; Gleim et al., 1990; Jones, 2002).

In contrast, other research fails to support the existence of an inverse relationship, countering that flexibility is an essential component of distance running performance (Beaudoin & Whatley Blum, 2005; Godges et al., 1989; Godges, MacRae, & Engelke, 1993; Nelson, Kokkonen, Eldredge, Cornwell, & Glickman-Weiss, 2001). Godges et al. (1989) found improved running economy at 40%, 60%, and 80% VO_2max in response to static stretching procedures in 7 moderately trained athletic male college students when flexibility increased (Godges et al., 1989). They reported a reduced aerobic demand of running at all speeds when hip flexion and extension were increased (Godges et al., 1989). Improved hip flexibility, myofascial balance, and pelvic symmetry due to stretching are thought to enhance neuromuscular balance and contraction, thus leading to a lower submaximal VO_2 and improved running economy. These results corroborate general beliefs that improved flexibility is desirable for optimal running performance.

Conflicting results among studies may be associated with limitations in methodological design. Several studies (Gleim et al., 1990; Godges et al., 1989; Godges et al., 1993) did not employ an adequate treadmill acclimatization period; therefore improvements in running economy may have been associated with familiarization with treadmill running (Craib et al., 1996). Furthermore, subjects were not described as runners of any caliber in several studies (Gleim et al., 1990; Godges et al., 1989; Godges et al., 1993; Nelson et al., 2001). Therefore lack of familiarity with treadmill running mechanics may have made economy measures invalid in these studies. Additionally, some studies (Gleim et al., 1990; Nelson et al., 2001; Trehearn & Buresh, 2009) have combined males and females results in the analyses; because females are generally more flexible (Trehearn & Buresh, 2009) and less economical

than males (Daniels & Daniels, 1992); the true association between economy and flexibility may be difficult to discern if genders are not studied separately. Finally, a recent systematic review concluded that an acute bout of stretching may improve running economy, but regular stretching prior to running over time has no effect on economy (Shrier, 2004). Overall these findings suggest stretching should not be discounted as a training modality, because stretching exercises are commonly prescribed for runners to facilitate injury prevention and maximize stride length (Bonacci et al., 2009; Saunders, Pyne, et al., 2004a). However, it appears that there could be an optimal degree of flexibility and stiffness or tightness required to maximize running economy.

3.7 Nutritional Interventions

Beyond the typical endurance athlete preparation, which features large amounts of aerobic training, high-intensity interval training, resistance and/or plyometric training, and various environmental exposures during a periodized season (Stellingwerff, 2013), several nutritional interventions have received attention for their effects on reducing oxygen demand during exercise, most notably dietary nitrates.

3.7.1 Dietary Nitrate

Nitric oxide (NO) is an important physiological signaling molecule that can modulate skeletal muscle function through its role in the regulation of blood flow, muscle contractility, glucose and calcium homeostasis, and mitochondrial respiration and biogenesis (Jones, 2013). It is now known that tissue concentrations of nitrate (NO_3^-) and nitrite (NO_2^-) can be increased by dietary means. Green leafy vegetables such as lettuce, spinach, rocket, celery and beetroot are particularly rich in nitrate. Therefore dietary nitrate supplementation represents a practical method to increase circulating plasma nitrite and thus nitric oxide to lower the oxygen demand of submaximal exercise (i.e. enhances metabolic efficiency and subsequently running economy) and potentially enhance running performance (Bailey, Fulford, et al., 2010; Bailey et al., 2009; Bailey, Winyard, et al., 2010; Jones, 2013; Jones, Bailey, & Vanhatalo, 2012; Jones, Vanhatalo, & Bailey, 2013; Larsen et al., 2011; Larsen, Weitzberg, Lundberg, & Ekblom, 2007). The physiological mechanisms responsible for the reduced oxygen demand following nitrate supplementation at the same running velocity could result from either a lower ATP cost of muscle contraction for the same force production (i.e., improved muscle contractile efficiency via effects on sarcoplasmic reticulum calcium handling or actin-myosin interaction) and/or a lower oxygen consumption for the same rate of oxidative ATP resynthesis (i.e., enhanced mitochondrial efficiency via improved oxidative phosphorylation) (Jones, 2013; Jones et

al., 2012; Jones et al., 2013).

While only one study to date has demonstrated an improved running economy (Lansley, Winyard, Fulford, et al., 2011) following nitrate supplementation, a reduced oxygen demand and improved work efficiency has been reported for several other types of exercise including cycling (Bailey et al., 2009; Larsen et al., 2007; Larsen, Weitzberg, Lundberg, & Ekblom, 2010; Vanhatalo et al., 2010), walking (Lansley, Winyard, Fulford, et al., 2011), and knee extension exercise (Bailey, Fulford, et al., 2010; Fulford et al., 2013). Larsen et al. (2007) reported that three days of sodium nitrate supplementation increased plasma nitrite and reduced the oxygen demand of submaximal cycling exercise (Larsen et al., 2007). These findings were corroborated by Bailey et al. (2009) in which nitrate was administered in the form of beetroot juice (Bailey et al., 2009). The reduction in VO_2 after nitrate supplementation was of the order of 5% in the studies of Larsen et al. (2007) and Bailey et al. (2009) in which supplementation was continued for 3-6 days (Bailey et al., 2009; Larsen et al., 2007). A similar reduction in steady-state VO_2 has been reported following acute nitrate supplementation. Vanhatalo et al. (2010) reported a significant reduction in steady-state VO_2 just 2.5 h following beetroot juice ingestion (Vanhatalo et al., 2010). Dietary nitrate supplementation has been reported to extend the time to exhaustion during high-intensity constant work rate exercise by 15-25% during cycle ergometry (Bailey et al., 2009; Vanhatalo et al., 2010), treadmill running (Lansley, Winyard, Fulford, et al., 2011), and two-legged knee extensor exercise (Bailey, Fulford, et al., 2010), and to enhance cycling performance over 4, 10, and 16.1 km by 1-2% (Lansley, Winyard, Bailey, et al., 2011) and 5-km time-trial running performance by 2.4% (Lanceley, Ranchordas, & Ruddock, 2013).

There is a paucity of data examining the effects of other dietary intervention on running economy. One investigation found four weeks of oral Echinacea supplementation enhanced running economy by 1.7% (Whitehead et al., 2012). Results from a study examining caffeine ingestion in cross-country runners suggest that the ingestion of caffeine at $7 \text{ mg}\cdot\text{kg}^{-1}$ of body weight prior to submaximal running might provide a modest ergogenic effect via improved respiratory efficiency and a psychological lift (Birnbaum & Herbst, 2004). Combined creatine and glycerol ingestion has been shown to be an effective means in reducing thermal and cardiovascular strain during exercise in the heat without negatively impacting on running economy (Beis et al., 2011). Although dietary nitrate appears to be a promising ergogenic aid, additional research is required to determine the scope of its effects on well-trained distance runners and across different competition events. Future research should also examine

the efficacy of using other nutritional interventions to enhance running economy.

3.8 Conclusions and Future Directions

A variety of training strategies have been adopted in an attempt to improve running economy by modifying one or more factors that influence metabolic, biomechanical and/or neuromuscular efficiency. Resistance training, plyometric and explosive resistance training have been reported to improve running economy in recreational, moderately trained, and high trained runners through primarily neuromuscular mechanisms. Results from high-intensity interval training studies are unclear, but the best results appear to occur when training at near maximal or supramaximal intensities. Uphill interval training and running in sand appear to be worthwhile training approaches as well, however more research is needed in this area. Adaptations to living and training at natural and artificial altitude have been primarily attributed to increased hematological parameters that improve running economy. Training in warm to hot conditions is another strategy to improve running economy, however interventions examining its efficacy are limited. There appears to be equivocal results regarding the effects of stretching or flexibility on running economy. Ingestion of dietary nitrate, especially in the form of beetroot juice, also appears to hold promise as a natural means to improve running economy. From a practical standpoint, it's clear that training and passive interventions affect running economy and researchers should concentrate their investigative efforts on more fully understanding the types and mechanisms which affect running economy and the practicality and extent to which running economy can be improved outside the laboratory.

CHAPTER 4: LOWER BODY DETERMINANTS OF RUNNING ECONOMY IN MALE AND FEMALE DISTANCE RUNNERS

4.1 Abstract

A variety of training approaches have been shown to improve running economy in well-trained athletes. However, there is a paucity of data exploring lower-body determinants that may affect running economy as well as account for differences that may exist between genders. Sixty-three male and female distance runners were assessed in the laboratory for a range of metabolic, biomechanical and neuromuscular measures potentially related to running economy ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) at a range of running speeds. At all common test velocities women were more economical than men (effect size (ES) = 0.40), however, when compared in terms of relative intensity males had better running economy (ES = 2.41). Leg stiffness ($r = -0.80$) and moment arm length ($r = 0.90$) were large to extremely largely correlated with running economy and each other ($r = -0.82$). Correlations between running economy and kinetic measures (peak force, peak power and time to peak force) for both genders were unclear. The relationship in stride rate ($r = -0.27$ to -0.31) was in the opposite direction to that of stride length ($r = 0.32$ to 0.49), and the relationship in contact time ($r = -0.21$ to -0.54) was opposite of that of flight time ($r = 0.06$ to 0.74). While both leg stiffness and moment arm length are highly related to running economy, it appears that no single lower-body measure can completely explain differences in running economy between individuals or genders. Running economy is therefore likely determined from the sum of influences from multiple lower-body attributes.

4.2 Introduction

Running economy is defined as the steady-state oxygen consumption (VO_2) at a given running velocity (Saunders, Pyne, et al., 2004a), therefore, a lower VO_2 at a given velocity would indicate better running economy. Runners with good running economy tend to run faster at a given distance or longer at a constant velocity than runners with poor running economy, assuming their $\text{VO}_{2\text{max}}$ is the same. Despite the performance benefits of being an economical runner, researchers have yet to resolve why some runners demonstrate markedly better economy when compared to counterparts exhibiting similar fitness, training history and performance backgrounds (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Daniels, Krahenbuhl, et al., 1977; Williams & Cavanagh, 1987).

A number of physiological, biomechanical and neuromuscular factors appear to influence running economy in well-trained or elite runners. These include metabolic adaptations within the muscle such as increased mitochondria and oxidative enzymes (Holloszy et al., 1977), more efficient mechanics leading to less energy wasted on braking forces and excessive vertical oscillation (Cavanagh et al., 1977; Williams & Cavanagh, 1987), and the ability of muscles to store and release elastic energy by increasing the lower-body stiffness (Dalleau et al., 1998). Furthermore, a variety of modifiable (e.g. percent body fat, body mass) (Anderson, 1996; Pate et al., 1992) and un-modifiable (e.g. Achilles moment arm length, height, skeletal structure) (Anderson, 1996; Raichlen et al., 2011; Scholz et al., 2008) anthropometric measures influence biomechanical and neuromuscular efficiency and subsequently alter running economy. For example, the amount of energy stored in a tendon depends on the mechanical properties of the tendon and on the force that stretch the tendon. Thus, for a given movement pattern, tendon force is inversely related to the moment arm of the Achilles tendon (Scholz et al., 2008). Since it is generally accepted that storage and reutilization of elastic energy in tendons substantially reduces energy demands in running (Cavagna & Kaneko, 1977) previous research has been able to establish a relationship between the variation in running economy and the moment arm of the Achilles tendon (Raichlen et al., 2011; Scholz et al., 2008), albeit in small sample sizes of 8 to 15.

Recent research has focused on various neuromuscular or biomechanical characteristics as mechanisms to explain improvements in running economy (Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003). Any lower-body adaptations which allows for improved muscle power development, enhanced ability of the muscles to store and release elastic energy by increasing stiffness, or more efficient mechanics

characterized by more skilled control of movement and muscle recruitment patterns (Anderson, 1996; Bonacci et al., 2009; Jung, 2003) could certainly explain differences in running economy among runners. The differences in running economy that exist between males and females has been previously investigated, but with mixed findings (Bransford & Howley, 1977; Daniels, Krahenbuhl, et al., 1977; Davies & Thompson, 1979; Maughan & Leiper, 1983; Morgan et al., 1995; Morgan & Craib, 1992). Research has yet to explore which of these lower-body characteristics can explain these inter-individual differences in running economy between male and female trained distance runners. Therefore, the present study was designed to evaluate the lower-body determinants of running economy among well-trained male and female distance runners.

4.3 Methods

4.3.1 Experimental Approach to the Problem

Male and female distance runners physiological, biomechanical and neuromuscular characteristics were assessed in our laboratory over a 3-year period. Testing took place during the competition phase of each runner's track or cross-country seasons. Most athletes were tested on one or more occasions during this time span. When more than one set of data was available for any athlete, the mean of all tests was used to represent that athlete. Obtaining measures during the competition phase for a range of competitive runners enabled us to characterize the lower body determinants or running economy at peak fitness levels.

4.3.2 Subjects

Sixty-three runners were assessed in our laboratory over a three-year period. All runners competed at the collegiate or national level. The athletes were all well-trained distance runners competing in events ranging from 800-m to 10-km with 27 runners qualifying for national championships in cross-country, track or road races, winning 13 national titles and 5 competing at the international level over a three-year testing period. Descriptive characteristics of the runners are presented in Table 6. The study was approved by the Auckland University of Technology Ethics Committee; Auckland, New Zealand. All participants provided informed written consent to participate.

Table 6: Subject and training characteristics*

	N	Age (y)	Body mass (kg)	VO ₂ max (ml·kg ⁻¹ ·km ⁻¹)	Training history (y)	Training volume (km·wk ⁻¹)	Peak speed (km·hr ⁻¹)
Male	39	20.8 ± 2.8	67.8 ± 6.8	68.7 ± 4.8	6.9 ± 2.9	97.2 ± 21.0	21.1 ± 1.6
Female	24	20.5 ± 2.1	55.0 ± 5.5	59.9 ± 3.5	6.9 ± 2.1	74.2 ± 12.7	19.4 ± 1.2

*Mean ± SD

4.3.3 Procedures

4.3.3.1 Submaximal and Maximal Aerobic Measures

Each test session included a series of 4-min submaximal runs on a motorized treadmill (PowerJog, Birmingham, UK) set at a 1.0% gradient until participants were clearly no longer able to sustain a steady-state VO₂ (ml·kg⁻¹·min⁻¹) (i.e. a slow component was evident), as determined visually from real-time plots of VO₂ followed by a fixed speed incremental test to determine VO₂max. Submaximal test velocities ranged from 12 to 18 km·h⁻¹ and expired gases were measured continuously using a metabolic cart (ParvoMedics TrueOne 2400, Salt Lake City, USA). Post-test data analysis, revealed that the maximum velocity at which steady-state VO₂ was achieved across the entire range of male and female subjects was 14 km·h⁻¹ and was therefore used to make comparisons between genders. Running economy was defined as the mean VO₂ determined during the last minute of each running speed and expressed in units relative to body mass and time (ml·kg⁻¹·min⁻¹). A lower VO₂ at any given running velocity would be indicative of a better (or improved) running economy. In our laboratory, the typical error of measurement of submaximal VO₂ was 1.8% (Barnes, Hopkins, et al., 2013b). Heart rate was determined every 1 s (Polar RS800sd, Polar Electro, Finland). Approximately 2-min following the last submaximal run, the incremental test was performed, using a velocity 1.0 km·h⁻¹ below each participant's final submaximal run speed. Treadmill gradient was increased by 1% each minute until volitional exhaustion. The highest VO₂ over a 30 s period during the test was considered VO₂max. Endurance performance was indicated by the peak running speed reached at the end of the incremental treadmill test. Because we used increases in gradient (rather than speed) in the latter part of the treadmill test, we calculated speed on the flat as $S = S_T + (S_T \times 0.045) \times i$; where S = peak speed in km·h⁻¹, S_T = treadmill speed in km·h⁻¹, and i = treadmill inclination in percent (Brooks, Fahey, & White, 1996). Biomechanical measures (stride rate, stride length, contact time, and flight time) were determined using high-speed video analysis during treadmill testing.

4.3.3.2 Neuromuscular Measures

Following the submaximal and maximal aerobic measures, participants performed a series of jump tests [countermovement jump (CMJ), squat jump (SJ), and 5-jump plyometric test (5J) involving five continuous vertical straight-leg jumps in which subjects were instructed to aim for maximal height with contact times as short as possible, keeping legs straight and arms still throughout the jumping sequence] on an AccuPower force plate (Advanced Mechanical Technology Inc., Watertown, MA) to determine neuromuscular characteristics previously described in the literature (McGuigan et al., 2006; Spurrs et al., 2003). The following parameters were determined for each type of jump: peak force, time to peak force, peak power and displacement. Eccentric utilization ratio (EUR) and stiffness were also calculated from the aforementioned parameters. Eccentric utilization ratio is an indicator of SSC ability in a variety of sports and during different phases of training (McGuigan et al., 2006). The EUR was calculated as the peak power ratio between performance on the CMJ compared to the SJ (McGuigan et al., 2006). Stiffness was estimated by dividing the relative peak force ($\text{N}\cdot\text{kg}^{-1}$) by the vertical displacement (m) measured during the 5-jump plyometric test as previously described by Cavagna et al. (Cavagna, Franzetti, Heglund, & Willems, 1988).

4.3.3.3 Moment Arm of the Achilles tendon

Methods for measuring the moment arm of the Achilles tendon followed those of Scholz et al. (2008) (Scholz et al., 2008). Briefly, we marked the most prominent aspect of the tip of the medial and lateral malleoli and took standardized photographs (Casio Exilim Pro Ex-F1; Casio Computer Co., Shelton, CT) of the medial and lateral sides of the foot while aligned with the reference block (Figure 7). The horizontal distance from the marked spot to the posterior aspect of the Achilles tendon was determined on the picture. The moment arm was taken to be the mean of these two distances.

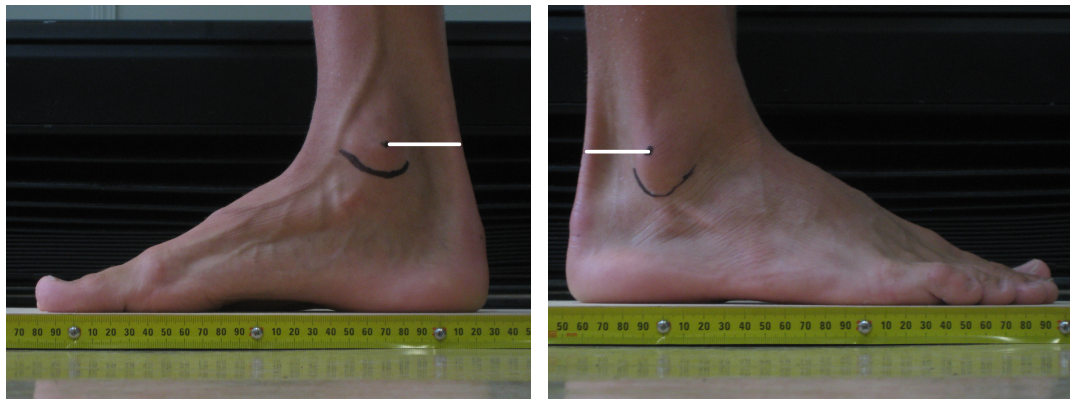


Figure 7: Standardized picture of the medial and lateral sides of the right foot, placed on, and aligned with a reference block. The horizontal distance from the medial and lateral malleolus to the Achilles tendon was determined (white lines). Moment arm was calculated as the mean of these two distances.

4.3.3.4 Statistical Analyses

Pearson's product moment correlation coefficient was used to determine relationships between running economy and functional lower body measures using SPSS (IBM SPSS Version 19.0; Chicago Illinois). Resulting correlation coefficients were converted into 90% confidence limits using a spreadsheet (Hopkins, 2007a). The threshold values for small, moderate, large, very large and extremely large magnitudes were 0.1, 0.3, 0.5, 0.7, and 0.9 of the correlation coefficient. The relationship between running economy and Achilles tendon moment arm was fitted with a non-linear model of the form $y=ax^{-2}+b$, following Scholz et al. (2008) which corresponds to the model of spring mechanics (assuming a linear spring where $n = 1$) (Scholz et al., 2008) previously shown to predict running economy in humans (Raichlen et al., 2011; Scholz et al., 2008). Comparisons of the differences between genders were made using a spreadsheet to calculate effect size and the magnitude of differences were evaluated non-clinically (Hopkins et al., 2009): if the confidence interval overlapped thresholds for substantial positive and negative values (± 0.20 standardized units, i.e., 0.20 of the between-subject SD of the dependent in the pre-test), the effect was deemed unclear; all other effects were reported as the magnitude of the observed value and were evaluated probabilistically with threshold values of 0.20, 0.60, 1.2, 2.0 and 4.0 for small, moderate, large, very large and extremely large respectively (Hopkins, 2007b; Hopkins et al., 2009). The probabilities were reported qualitatively using the following scale: 25-75%, possibly; 75-95%, likely; 95-99.5%, very likely; >99.5%, most likely (Hopkins et al., 2009).

4.4 Results

Descriptive characteristics of the runners are presented in Table 6. There was no difference between males and females in age or training history, a large difference in training volume and peak speed and very large difference between body mass, and VO_{2max} .

Aerobic profiles generated from the mean economy curves of male and female runners are shown in Figure 8. At all common test velocities women were more economical (lower VO_2) than men ($p = 0.13$, $ES = 0.40$). However, the combination of a very large difference in VO_{2max} ($p < 0.001$, $ES = 2.95$) and similar economy slopes resulted in a large difference ($p < 0.001$, $ES = 1.91$) in vVO_{2max} . When men and women were compared in terms of relative intensity at common running velocities (Figure 8), males ran at a significantly lower percentage of their respective VO_{2max} es ($p < 0.001$, $ES = 2.41$).

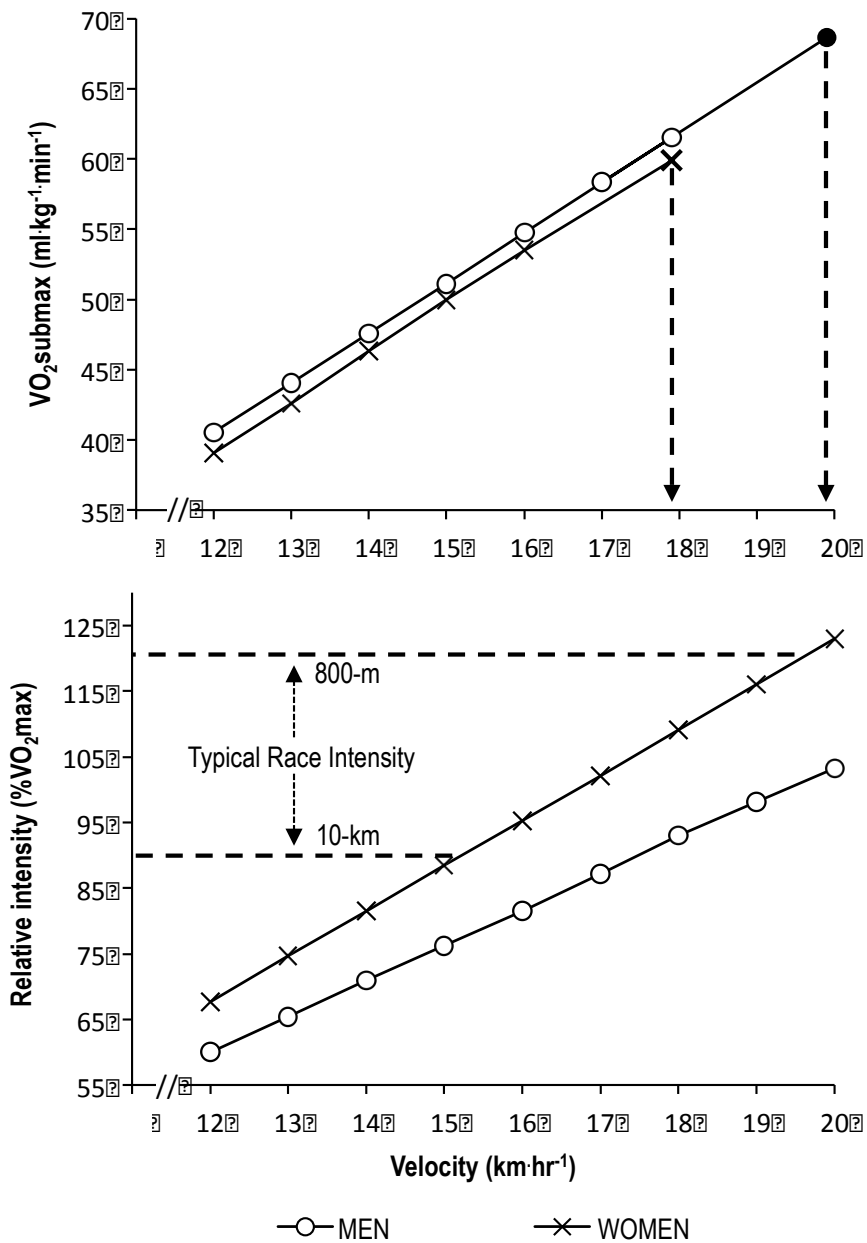


Figure 8: Aerobic profiles of male (n = 39) and female (n = 24) runners expressed in terms of relative O₂ consumption (VO₂submax) and relative intensity. Bold **x** and **•** indicate velocity at VO₂max (vVO₂max).

Table 7 shows the mean male and female outcome measures and magnitude of differences between genders. Females took moderately more strides per minute and had moderately shorter stride length as well as longer contact times and shorter flight times. There were large differences in Achilles moment arm length, stiffness and jump height (Table 7) between genders. Males produced greater peak force and peak power than females and the differences were of small and large magnitude, respectively. There were no clear differences in CMJ peak force between genders.

Female's time to peak force was moderately faster than males, except in the CMJ measure, which was unclear. Differences in EUR were unclear.

Table 7: Mean male and female biomechanical and neuromuscular outcome measures and statistics for effects and inferences between genders.

	Male (n = 39) (mean ± SD)	Female (n = 24) (mean ± SD)	Group comparison (Female - Male)	
			Difference between groups (% ±CL)	Qualitative inference (ES) ^a
Biomechanical Measures				
Stride rate (strides·min ⁻¹)	85.6 ± 4.8	90.2 ± 4.5	5.4 ±2.3	moderate** (0.97)
Stride length (m)	2.89 ± 0.21	2.66 ± 0.21	-8.0 ±3.3	moderate*** (1.10)
Contact time (s)	0.23 ± 0.02	0.24 ± 0.02	2.9 ±3.5	small* (0.36)
Flight time (s)	0.12 ± 0.02	0.10 ± 0.02	-20.5 ±8.3	large* (1.29)
Moment arm (cm)	4.4 ± 0.6	3.5 ± 0.5	-21.6 ±6.1	large*** (1.78)
Neuromuscular Measures				
EUR	1.01 ± 0.06	1.02 ± 0.12	0.0 ±4.3	unclear (0.00)
Stiffness (kN·m ⁻¹)	9.4 ± 2.2	13.3 ± 2.7	41.3 ±10.9	large** (1.44)
Jump height (m)	0.49 ± 0.14	0.30 ± 0.10	-39.2 ±13.7	large*** (1.67)
Countermovement Jump				
Peak force (N·kg ⁻¹)	61.6 ± 15.3	61.3 ± 14.6	-0.3 ±10.5	unclear (0.01)
Peak power (W·kg ⁻¹)	45.1 ± 5.4	38.0 ± 5.8	-16.2 ±6.5	large* (1.24)
Time to peak force (s)	2.19 ± 0.52	2.16 ± 0.42	0.6 ±9.1	unclear (0.03)
Squat Jump				
Peak force (N·kg ⁻¹)	57.2 ± 11.9	52.9 ± 11.2	-7.9 ±9.8	small** (0.38)
Peak power (W·kg ⁻¹)	44.8 ± 5.1	37.6 ± 5.0	-16.2 ±5.7	large** (1.40)
Time to peak force (s)	2.60 ± 0.60	2.24 ± 0.38	-12.4 ±9.5	moderate* (0.60)
5-Jump Test				
Peak force (N·kg ⁻¹)	64.9 ± 9.2	68.4 ± 11.1	5.0 ±7.2	small* (0.31)
Peak power (W·kg ⁻¹)	68.9 ± 16.5	51.8 ± 10.7	-24.2 ±10.5	moderate*** (1.16)
Time to peak force (s)	3.23 ± 0.72	2.68 ± 0.52	-16.5 ±9.4	moderate** (0.85)

CL = confidence limits; ES = effect size; EUR = eccentric utilization ratio.

*25-75%, possible; **75-95%, likely; ***95-99.5%, very likely; ****>99.5%, most (or extremely) likely

^a<0.2 trivial; ≥0.2 small; ≥0.6 moderate; ≥1.2 large; ≥2.0 very large; ≥4.0 extremely large

The correlations between running economy and lower body characteristics for male and female runners are provided in Table 8. Generally the relationship among biomechanical measures was small to moderate in males, except flight time which was unclear and moderate-large in females. For males and females the relationship in stride rate (negative) was in the opposite direction to that of stride length (positive), and the relationship in contact time (negative) was opposite of that of flight time (positive). There was a large positive relationship between running economy and moment arm length in both male and female runners (Table 8); and this relationship was stronger (extremely large) when this data was combined ($r = 0.90$; 90% confidence interval 0.85 to 0.93, Figure 9). All relationships between EUR and running economy were unclear. There was a moderate and large negative correlation between muscle stiffness and running economy (Table 8), in males and females, respectively. This relationship was slightly higher when male and female data was combined ($r = -0.80$; -0.86 to -0.71, Figure 9). Muscle stiffness was also largely negatively related to moment arm length (-

0.82; -0.88 to -0.74, Figure 9). There were moderate and large correlations between running economy and jump height in males and females respectively. Most other correlations between running economy and jump related measures (peak force, peak power and time to peak force) for males and females were unclear (Table 8).

Table 8: Correlations between running economy ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and lower body characteristics in male and female distance runners.

	Male (n = 39)		Female (n = 24)	
	Correlation ^a with 90% \pm CL	Qualitative inference	Correlation ^a with 90% \pm CL	Qualitative inference
Biomechanical Measures				
Stride rate ($\text{strides}\cdot\text{min}^{-1}$)	-0.27 \pm 0.25	-ive**	-0.31 \pm 0.31	-ive**
Stride length (m)	0.32 \pm 0.24	+ive**	0.49 \pm 0.19	+ive****
Contact time (s)	-0.21 \pm 0.26	-ive*	-0.54 \pm 0.25	-ive**
Flight time (s)	0.06 \pm 0.27	unclear	0.74 \pm 0.17	+ive****
Moment arm (cm)	0.82 \pm 0.09	+ive****	0.81 \pm 0.13	+ive****
Neuromuscular Measures				
EUR	0.04 \pm 0.27	unclear	-0.02 \pm 0.34	unclear
Stiffness ($\text{kN}\cdot\text{m}^{-1}$)	-0.57 \pm 0.19	-ive****	-0.76 \pm 0.16	-ive****
Jump height (m)	0.39 \pm 0.23	+ive***	0.66 \pm 0.21	+ive****
Countermovement Jump				
Peak force ($\text{N}\cdot\text{kg}^{-1}$)	-0.14 \pm 0.37	unclear	0.05 \pm 0.34	unclear
Peak power ($\text{W}\cdot\text{kg}^{-1}$)	-0.14 \pm 0.37	unclear	0.28 \pm 0.32	+ive**
Time to peak force	0.21 \pm 0.26	+ive*	0.20 \pm 0.33	unclear
Squat Jump				
Peak force ($\text{N}\cdot\text{kg}^{-1}$)	0.28 \pm 0.25	+ive**	0.03 \pm 0.34	unclear
Peak power ($\text{W}\cdot\text{kg}^{-1}$)	-0.04 \pm 0.27	unclear	0.38 \pm 0.30	+ive**
Time to peak force	0.17 \pm 0.26	unclear	0.16 \pm 0.34	unclear
5-Jump Test				
Peak force ($\text{N}\cdot\text{kg}^{-1}$)	-0.19 \pm 0.26	-ive*	-0.03 \pm 0.34	unclear
Peak power ($\text{W}\cdot\text{kg}^{-1}$)	-0.06 \pm 0.27	unclear	0.59 \pm 0.24	+ive****
Time to peak force	0.05 \pm 0.27	unclear	0.16 \pm 0.34	unclear

*25-75%, possible; **75-95%, likely; ***95-99.5%, very likely; ****>99.5%, most (or extremely) likely
^a<0.0 trivial; \geq 0.1 small; \geq 0.3 moderate; \geq 0.5 large; \geq 0.7 very large; \geq 0.9 extremely large; 1.0 perfect

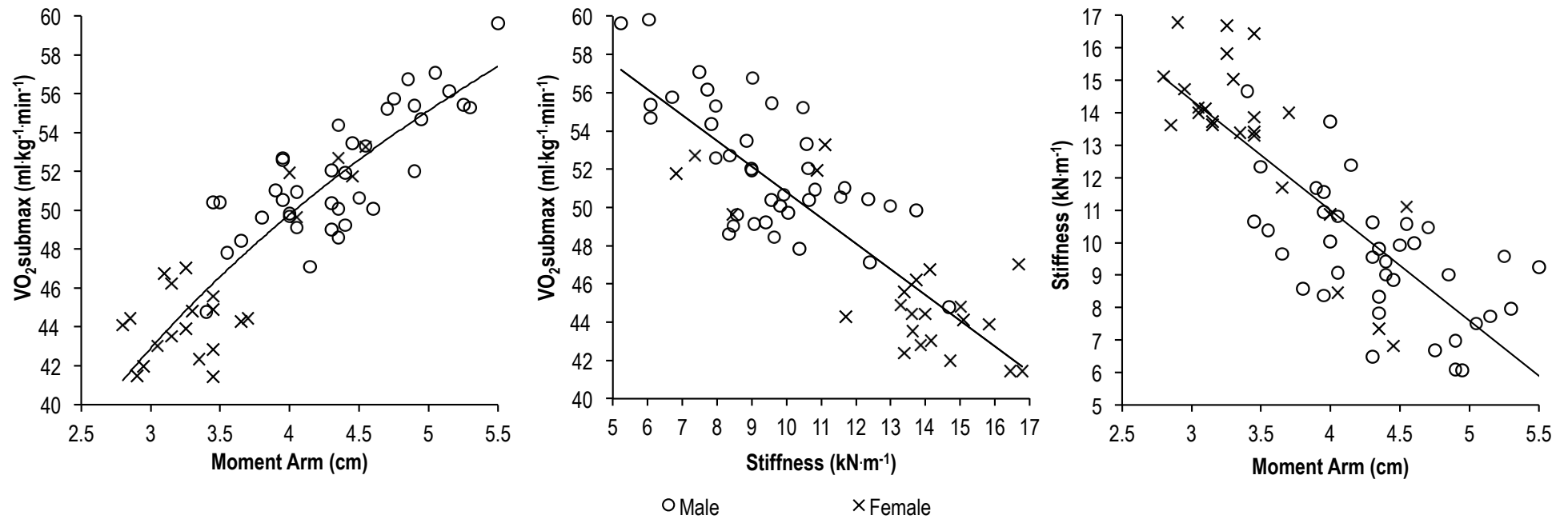


Figure 9: Correlation between running economy at $14 \text{ km} \cdot \text{hr}^{-1}$ and Achilles moment arm length ($r = 0.90$), running economy at $14 \text{ km} \cdot \text{hr}^{-1}$ and leg stiffness ($r = -0.80$), and leg stiffness and Achilles moment arm length ($r = -0.82$) for all runners.

4.5 Discussion

In the current study, we compared specific anthropometric, neuromuscular and biomechanical lower-body measures, and explored relationships between measures in a large sample of well-trained male and female distance runners in an attempt to identify key determinants of running economy. Athletes such as distance runners rely on efficient utilization of available energy to facilitate optimum performance. The results of this investigation suggest that differences in running economy between distance runners appear in part to be the result of select modifiable and non-modifiable lower body characteristics, which may also explain differences in performance.

4.5.1 Leg Stiffness

It is well known that stiffer muscles, or tendons, are more economical at transferring energy (Cavagna & Kaneko, 1977; Dalleau et al., 1998; Lichtwark & Wilson, 2008; Spurr et al., 2003). The stiffness values in our 63 well-trained runners (male: $9.4 \text{ kN}\cdot\text{m}^{-1}$, female: $13.3 \text{ kN}\cdot\text{m}^{-1}$) were similar to those of Dumke et al. (Dumke, Pfaffenroth, McBride, & McCauley, 2010) ($11.8 \text{ kN}\cdot\text{m}^{-1}$) and Fukashiro et al. (Fukashiro, Noda, & Shibayama, 2001) ($9.6 \text{ kN}\cdot\text{m}^{-1}$) utilizing well-trained and untrained men and women, respectively. Similar to other studies (Arampatzis et al., 2006; Dumke et al., 2010), the present data demonstrated that lower body stiffness is substantially related to running economy of well-trained runners (Table 8, Figure 9). While it remains to be determined the trainability of stiffness across varying levels of fitness, emerging evidence suggest runners and coaches may want to focus on strategies to improve lower body stiffness to enhance performance. Indeed, previous evidence has also shown that running economy is strongly related to performance times at distances greater than 800 m (Conley & Krahenbuhl, 1980; Morgan, Baldini, et al., 1989). This study also showed that lower body stiffness was related to the moment arm of the Achilles tendon (Figure 9). This is a unique finding not previously reported in the literature and suggests the Achilles moment arm may affect stiffness properties following training. The relationship between resistance training and/or plyometric training and running economy is not a new concept. In fact, several research investigations have shown that strength training (both high resistance and explosive) can improve running economy by modulating lower body stiffness (Barnes, Hopkins, et al., in press; Paavolainen, Hakkinen, et al., 1999; Spurr et al., 2003).

4.5.2 Moment Arm

Our data revealed a substantial relationship between running economy and the

moment arm of the Achilles tendon. This relationship was anticipated based on a simple musculoskeletal model of tendon energy storage (Scholz et al., 2008) but the magnitude of this relationship ($r = 0.90$, Figure 9) was considerably larger than previously reported by Raichlen et al. ($r = 0.64$, $n = 8$) (Raichlen et al., 2011) and Scholz et al. ($r = 0.77$, $n = 15$). This finding supports the premise that storage and release of elastic strain energy in the Achilles tendon plays an important role in reducing the energy cost of running. This spring-like action of the Achilles tendon during running means that individuals with smaller (shorter) moment arms stretch their Achilles tendons to a greater degree and therefore convert a higher percentage of kinetic energy into elastic energy, which is then returned to the propulsive forces of the stance leg. The energy generated by the contractile machinery of the lower body is metabolically the most expensive process in muscle contraction (Scholz et al., 2008) thus any energy stored in the tendon that does not have to be generated during muscle contraction results in a lower energy cost of running. Previous research indicates that variations in moment arm explained 56% (Scholz et al., 2008) and 64% (Raichlen et al., 2011) of the variation in running economy among runners. Although Achilles moment arm length is a non-modifiable factor affecting running economy, for practitioners this is an easy determinant to measure and may help scientists and coaches understand why some athletes have good or poor economy and may also be a determinant of the upper and lower limits of an individual's ability to improve their running economy.

4.5.3 Neuromuscular Characteristics

The findings from previous studies suggest that neuromuscular characteristics may play an important role in running economy, especially in athletes with similar physiological attributes (Bonacci et al., 2009; Johnston et al., 1997; Paavolainen, Hakkinen, et al., 1999). However, our results suggest that most neuromuscular characteristics, at least those measured in this study, have an unclear or small relationship with running economy. In previous studies, the timing and amplitude of muscle activity has shown the most consistent association with running economy (Dalleau et al., 1998; Kyrolainen et al., 2001; Nummela et al., 2008; Paavolainen, Nummela, Rusko, et al., 1999; Paavolainen, Nummela, & Rusko, 1999). Measurements of electromyographic (EMG) muscle activity were beyond the scope of this study, but upon greater inspection, most of the previous studies indicate that greater muscle activity prior to and in the initial phase of ground contact may enhance running economy by increasing leg stiffness and maximizing exploitation of stored elastic energy. Leg stiffness is modulated by neuromuscular activation, and changes in

stiffness have been shown to occur as a result of neuromuscular adaptation to training (Franklin et al., 2003). It has been suggested that if the rate of force development and peak force is enhanced, a longer recovery period between muscle contraction is possible, leading to improved muscle blood perfusion and thereby improving running economy (Hoff et al., 1999; Osteras et al., 2002). Other authors suggest the ability of the neuromuscular system to repeatedly produce force rapidly may be an important determinant of running economy (Paavolainen, Nummela, & Rusko, 1999). Direct evidence to support this premise is limited and weak and while many of our lower body determinants were indirect measures of neuromuscular activity, we found no such relationships between these measures and running economy suggesting future research should concentrate on more direct measures of neuromuscular activity and running economy. Until more data is collected coaches and athletes should focus on interventions that increase lower body stiffness.

4.5.4 Biomechanical Characteristics

The results of previous studies have identified a number of biomechanical variables that relate to running economy including stride length that is freely chosen (Cavagna et al., 1991; Cavanagh et al., 1977; Cavanagh & Williams, 1982; Morgan, Martin, et al., 1994; Morgan & Martin, 1986; Williams & Cavanagh, 1987), low vertical oscillation of body center of mass (Cavanagh et al., 1977; Williams & Cavanagh, 1987), and low peak ground reaction forces (Williams & Cavanagh, 1987; Williams et al., 1987). In the present study, we considered the basic biomechanical characteristics most often reported in the literature. Stride length was moderately correlated with running economy in the present study. Relationships between running economy and stride length, expressed as an absolute or relative to height or leg length have also been low to moderate (Cavanagh et al., 1977; Cavanagh & Williams, 1982; Williams & Cavanagh, 1987). The most striking and ubiquitous finding regarding stride length and running is that a freely chosen stride length is most economical (Cavanagh & Kram, 1985a; Hogberg, 1952; Morgan, Martin, et al., 1994; Morgan & Martin, 1986; Williams et al., 1987). Experimentally induced deviations from this freely chosen stride length has invariably evoked increased oxygen cost (Cavanagh & Williams, 1982; Hogberg, 1952). There is a natural reciprocal relationship between stride length and stride rate, suggesting that runners naturally acquire an optimal stride rate based on perceived exertion (Cavanagh & Williams, 1982). It is not surprising then that stride rate was also small-moderately correlated with running economy. The balance between the time during which the foot is in contact with the ground (contact time) and not in contact with the ground (flight time) has been studied in relation to running economy, but with no

consistent findings. Likewise, we found small correlation between contact time and running economy in males and a large correlation in females; furthermore there was no correlation between flight time and running economy in males but very large correlation in females. Previous studies completed have found that longer contact times and shorter flight times were associated with poorer economy (Williams & Cavanagh, 1987) which our female results support, while others have found the opposite relationship (Nummela et al., 2007), and others no relationship (Cavanagh et al., 1977; Williams et al., 1987), which our male results support. There is an intuitive link between running mechanics and energy cost of running, but research to date has not established a clear mechanical profile of an economical runner. The results of the present study corroborate this statement. It appears that through training, individuals are able to integrate and accommodate their own unique combination of dimensions and mechanical characteristics so that they arrive at a running motion that is most economical for them.

4.5.5 Men vs. Women

Our running economy data, shown in Figure 8, is in disagreement with some (Bhambani & Singh, 1985; Bransford & Howley, 1977; Daniels & Daniels, 1992; Howley & Glover, 1974) but not all (Bunc & Heller, 1989; Davies & Thompson, 1979; Hopkins & Powers, 1982; Maughan & Leiper, 1983; Mayhew et al., 1979) previous investigations demonstrating that males are more economical (lower VO_2) than females when compared at common running velocities. However, when compared in terms of relative intensity, the males ran at a significantly lower percentage of their respective VO_{2max} compared to females (Figure 8). The comparison in terms of relative intensity is an important one because well-trained runners all perform at near equal percentages of their respective VO_{2max} depending on the distance of the event in question (Daniels & Daniels, 1992). Figure 8 presents these findings and demonstrates the magnitude of differences between genders is greater as the intensity of the competitive event increases. In an attempt to elucidate any gender differences in running economy, our comparison of the lower body determinants of running economy (Table 7) revealed substantial differences in biomechanical measures. Williams et al. (Williams et al., 1987) also showed that women were biomechanically different than men during running by demonstrating woman possess greater stride rates and shorter stride lengths compared to male counterparts. In the current study, males demonstrated greater peak force and peak power when normalized by body mass, while females have a faster time to peak force. This supports the finding that females have a substantially faster stride rate and short stride length. The increased energy costs from

a higher stride rate due to various kinetic and kinematic patterns involved in a faster gait cycle may be an explanation for why in some studies females are less economical than male runners.

In summary, despite some substantial correlations between some lower body measures and running economy, it appears that no single lower body measure can completely explain differences in running economy within and between genders. Other factors such as body lengths, mass distribution, fiber type, vertical oscillation, footstrike patterns, and other kinetic and kinematics are also likely to affect running economy. Running economy is therefore likely determined from the sum of influences from multiple lower-body attributes.

4.6 Practical Applications

Many of the lower body characteristics measured in this study represent specific or independent qualities of running economy that can be assessed and trained independently. Given the strong relationship between running economy and stiffness as indicated by our results, perhaps a greater efficiency of training can be achieved by targeting interventions that increase leg stiffness to improve running economy. The Achilles moment arm length is a non-modifiable determinant related to running economy and appears to provide the practitioner with information about the stiffness of the lower body which may elucidate an athlete's potential to improve their running economy, however more data is needed to validate this. The data we have presented here for a variety of lower body measures commonly measured in athletes gives an indication of normative ranges for well-trained male and female runners.

4.7 Acknowledgements

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CHAPTER 5: WARM-UP WITH A WEIGHTED VEST IMPROVES RUNNING PERFORMANCE VIA LEG STIFFNESS AND RUNNING ECONOMY

5.1 Abstract

A bout of resistance exercise can enhance subsequent high-intensity performance, but little is known about such priming exercise for endurance performance. **Objectives** To determine the effects of "strides" with a weighted-vest during a warm-up on endurance performance and its potential neuromuscular and metabolic mediators. **Design** A crossover with 5-7 days between an experimental and control trial was performed by 11 well-trained distance runners. **Methods** Each trial was preceded by a warm-up consisting of a 10-min self-paced jog, a 5-min submaximal run to determine running economy, and six 10-s strides with or without a weighted-vest (20% of body mass). After a 10-min recovery period, runners performed a series of jumps to determine leg stiffness and other neuromuscular characteristics, another 5-min submaximal run, and an incremental treadmill test to determine peak running speed. Clinical and non-clinical forms of magnitude-based inference were used to assess outcomes. Correlations and linear regression were used to assess relationships between performance and underlying measures. **Results** The weighted-vest condition resulted in a very-large enhancement of peak running speed (2.9%; 90% confidence limits $\pm 0.8\%$), a moderate increase in leg stiffness (20.4%; $\pm 4.2\%$) and a large improvement in running economy (6.0%; $\pm 1.6\%$); there were also small-moderate clear reductions in cardiorespiratory measures. Relationships between change scores showed that changes in leg stiffness could explain all the improvements in performance and economy. **Conclusions** Strides with a weighted-vest have a priming effect on leg stiffness and running economy. It is postulated the associated major effect on peak treadmill running speed will translate into enhancement of competitive endurance performance.

5.2 Introduction

Prior warm-up activities are a widely accepted practice preceding nearly every athletic event to prepare the body for optimal competition performance (Bishop, 2003). An active warm up is arguably the most widely used warm-up technique for distance runners because it is likely to induce specific metabolic and cardiovascular changes conducive to distance-running performance (Bishop, 2003). Recent research has focused on various warm-up exercises that can alter oxygen uptake (VO_2) kinetic responses to subsequent high-intensity exercise and enhance performance (Bishop et al., 2001; Hajoglou et al., 2005; Ingham et al., 2013). However, neuromuscular characteristics have also been recognized as an important determinant of endurance performance (Paavolainen, Hakkinen, et al., 1999). Indeed, different training regimens have demonstrated concomitant improvements in neuromuscular measures, running economy and distance running performance (Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003). Subsequently, the evaluation of neuromuscular characteristics has become an important consideration for running economy and performance, but no research has examined modifying these parameters acutely by different warm-up interventions to improve distance running performance.

Post-activation potentiation is a well-recognized phenomenon that involves the preconditioning of muscle through heavy exercise to induce acute improvements in performance during sprinting, running and weightlifting activities (Hodgson et al., 2005; Tillin & Bishop, 2009). A common method used by athletes to facilitate post-activation potentiation response is performing sport specific movement patterns while wearing a weighted vest that provides additional resistance to movement. Several studies have examined the long-term influence of training with such additional loads on various metabolic and lower-extremity parameters in various athletes with positive results (Bosco, Rusko, & Hirvonen, 1986; Bosco et al., 1984; Rusko & Bosco, 1987). Specifically in endurance runners, Rusko and Bosco (Rusko & Bosco, 1987) observed an improvement in running performance and peak speed in addition to a reduction in oxygen uptake during submaximal running after four weeks of wearing a weighted vest in 12 well-trained endurance athletes. The authors credited the increase in muscle activation as the principal explanation for the observed changes (Rusko & Bosco, 1987). It is unknown whether other short-term changes in muscle conditioning can be achieved acutely with bouts of high-intensity exercise while wearing a weighted vest for the purpose of performance enhancement. Therefore, the purpose of the present study was to determine the acute effects of wearing such a vest during warm-up "strides" (short-duration near-maximal sprints) on neuromuscular measures, running economy and distance running performance in trained runners.

5.3 Methods

Eleven well-trained male distance runners took part in the study. The mean \pm SD body mass: 67.4 ± 10.5 kg, height: 177.6 ± 10.4 cm, and age of subjects was 29.8 ± 4.3 y with an average training history of 8.4 ± 4.4 y and 5-km personal best of 16.0 ± 1.0 min. Subjects undertook 105.6 ± 30.9 km of running per week in the six weeks leading up to the study. The study was approved by the Auckland University of Technology Ethics Committee; Auckland, New Zealand, and all participants provided informed written consent to participate.

Athletes reported to the laboratory 2 hours post-prandial and having avoided strenuous exercise in the 24 hours preceding a test session. All running tests were performed in controlled laboratory conditions ($19\text{-}21^{\circ}\text{C}$; $65\%\text{rH}$) run on a motorized treadmill (HP Cosmos Saturn, Traunstein, Germany). Participants initial visit involved a familiarization session with all testing procedures and equipment. Thereafter, participants completed two incremental peak running speed performance trials (in a crossover experimental design), preceded by two different warm-up conditions, in random order, at the same time of day, separated by at least 5 days (Figure 10).

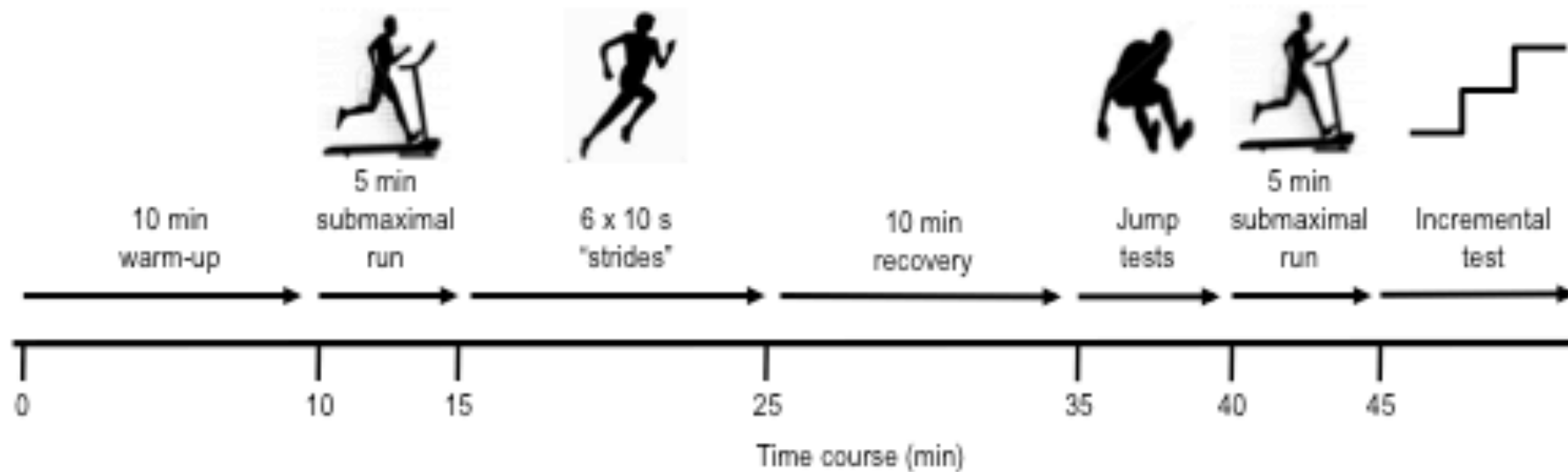


Figure 10: Schematic representation of crossover experimental design, indicating the control and weighted vest conditions. Two submaximal runs were included to assess differences in running economy and other submaximal measures within and between conditions. The 6 × 10 s strides and recovery period were completed in a cross-over manner. The 10-min recovery period was included to simulate the “holding” procedures that athletes often experience prior to major competitions. All other running and jump tests were completed at normal body weight. Jump tests were included to assess neuromuscular characteristics, and the incremental test assessed peak running speed and VO_2 max.

Each performance trial was preceded by a 10 min self-paced jog followed by 5 min bout of submaximal running at $14 \text{ km}\cdot\text{h}^{-1}$ (1.0% gradient) during which expired gas samples were measured continuously using a metabolic cart (ParvoMedics TrueOne 2400, Salt Lake City, USA) for determination of VO_2 , carbon dioxide production, minute ventilation and respiratory exchange ratio. Running economy, minute ventilation, respiratory exchange ratio and heart rate were determined from mean data during the last two minutes of each submaximal steady-state run. At the end of the submaximal steady-state run each subjects rating of perceived exertion (RPE) was assessed using a standardized Borg RPE scale (Borg, 1970).

Subsequently, in the control condition, participants performed 6×10 -s strides, with a walk-back recovery (~ 60 s). This warm-up procedure was similar to that which athletes would ordinarily complete prior to a competition. In the intervention trial, participants completed the same 6×10 -s strides while wearing a weighted vest that was equivalent to 20% of the subjects body mass. Runners understood that the speed of strides in the control and weighted-vest conditions were to be completed at each subject's ~ 1500 m race pace. The respective warm-up procedures were followed by 10 min of recovery, which was included to simulate the "holding" procedures that athletes often experience prior to major track competitions, followed by a series of jump tests to determine neuromuscular characteristics, then the peak-speed performance trial which commenced 15 min following the warm-up. Prior to the performance trial the participants "perceived race readiness" was assessed using the 1-10 scale of Ingham et al (Ingham et al., 2013).

The performance test involved a 5-min submaximal run at $14 \text{ km}\cdot\text{h}^{-1}$ (1.0% gradient) followed immediately by an incremental test. During the incremental portion of the performance test, the speed increasing by $1 \text{ km}\cdot\text{h}^{-1}$ every minute until a speed of $18 \text{ km}\cdot\text{h}^{-1}$ was reached, thereafter, the gradient increased by 1% every minute until volitional exhaustion. Each subjects RPE was reassessed at the end of the 5-min steady-state run. Heart rate and pulmonary gas-exchange were measured continuously. The peak speed reached at the end of the test was determined as: $S = S_T + (S_T \times 0.045) \times i$; where S = peak speed in $\text{km}\cdot\text{h}^{-1}$, S_T = treadmill speed in $\text{km}\cdot\text{h}^{-1}$, and i = treadmill inclination in percent (Brooks et al., 1996).

Subjects performed a series of jump tests [$2 \times$ countermovement jump (CMJ), squat jump (SJ), and 5-jump plyometric test (5J)] on an AccuPower force plate (Advanced Mechanical Technology Inc., Watertown, MA) to determine neuromuscular characteristics previously described in the literature (McGuigan et al., 2006; Spurrs et al., 2003). The best result from the following parameters was determined for each type

of jump: peak force, time to peak force, peak power and displacement. Eccentric utilization ratio (EUR) and stiffness were also calculated from the aforementioned parameters. The eccentric utilization ratio was calculated as the peak power ratio between performance on the CMJ compared to the SJ (McGuigan et al., 2006). Stiffness was estimated by dividing the relative peak force ($\text{N}\cdot\text{kg}^{-1}$) by the vertical displacement (m) measured during the 5-jump test (Cavagna et al., 1988).

The effects of warm-up condition on performance, physiological and neuromuscular measures were analyzed with a spreadsheet for post-only crossovers (Hopkins, 2006). The pre-test value of the dependent variable was included as a covariate to improve precision of the estimate of the effects. Submaximal running measures obtained during the 5-min submaximal run both pre and post warm-up (Figure 10) were also analyzed with a pre-post crossover spreadsheet (Hopkins, 2006). Effects were estimated in percent units via log transformation, and uncertainty in the estimate was expressed as 90% confidence limits. The effect size (ES), which represents the magnitude of the difference between the two conditions in terms of SD, was calculated from the log-transformed data by dividing the change in the mean by the average SD of the two conditions. The outcome for performance (peak speed) was evaluated with the clinical version of magnitude-based inference: the effect was deemed unclear if the chance of benefit was sufficiently high (>25%) to warrant its use with athletes but the risk of harm was unacceptable (>0.5%); the effect was otherwise deemed clear and reported as the magnitude of the observed effect and the qualitative probability that the true magnitude was at least as large as the observed magnitude. The threshold values for assessing the magnitude of small, moderate and large, very large and extremely large effects were respectively 0.3, 0.9, 1.6, 2.5 and 4.0 times the within-subject standard deviation a top athlete would show between competitions (Hopkins et al., 2009). For distance runners this standard deviation was 0.8%, (Hopkins, 2005) so the thresholds were 0.24%, 0.72%, 1.3%, 2.0% and 3.2%. Probabilities were reported using the following scale: 25-75%, possibly; 75-95%, likely; 95-99.5%, very likely; >99.5%, most likely. Magnitudes of effects on measures other than performance were evaluated non-clinically: if the confidence interval overlapped thresholds for small positive and negative values, the effect was deemed unclear; all other effects were reported as the magnitude of the observed value and were evaluated probabilistically as described above, except that threshold values for small, moderate, large, very large and extremely large effects were 0.2, 0.6, 1.2, 2.0 and 4.0 of the between-subject standard deviation in the control condition (Hopkins et al., 2009).

To analyze potential relationships underlying the effect of warm-up condition on performance, changes in performance were plotted against changes in mechanism variables and the scatterplots inspected for any linear trend. Resulting correlation coefficients were converted into 90% confidence limits using a spreadsheet (Hopkins, 2007a). The contribution of each of the physiological and neuromuscular measures to the change in performance (peak speed) was investigated by using the change scores of each log-transformed measure as a covariate in the spreadsheet for the analysis of the effect of the warm-up condition. The change in performance associated with the measure was given by evaluating the effect on performance of a difference in the covariate equal to the mean change in the measure, while the change in performance independent of the measure was given by adjusting the effect of the treatment to zero change in the measure (Hopkins, 2008; Hopkins et al., 2009). To investigate the extent to which leg stiffness explained the contribution of each other measure, leg stiffness was included as an additional covariate. These multiple linear regressions could not be performed with the post-only crossover spreadsheet but were realized instead with the Linest function in Excel.

5.4 Results

The effect on peak speed was very large relative to the thresholds for changes in performance time of top competitive athletes (Table 9), whereas the effect was only small (ES = 0.31) in relation to thresholds defined by standardization. The effect on VO₂max was clearly trivial (ES = 0.05). Individual and mean changes in peak speed are shown in Figure 11. For evaluation of individual responses in performance (see Discussion), the standard deviations of change scores for peak speed and VO₂max were 1.6% and 2.0% respectively.

Table 9: Mean and SD of performance and other measures following control and weighted-vest treatments, and inferences for percent change of the means.

	Control	Weighted Vest	Weighted vest – control	
			Mean change; $\pm 90\%CL$ (%)	Qualitative inference ^a
Performance Measures				
Peak speed (km·hr ⁻¹)	20.4 \pm 1.7	21.0 \pm 1.8	2.9; \pm 0.8	very large benefit**
VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	62.1 \pm 5.9	62.5 \pm 6.3	0.6; \pm 1.1	trivial***
Perceptual Measures				
Rating of perceived exertion (6-20)	12.4 \pm 1.0	11.0 \pm 1.2	-11.2; \pm 4.7	moderate +ive***
Perceived race readiness (1-10)	7.3 \pm 1.0	6.7 \pm 1.5	-9; \pm 10	small -ive**
Submaximal Running Measures				
VO ₂ submax (ml·kg ⁻¹ ·min ⁻¹)	46.1 \pm 2.0	43.3 \pm 2.1	-6.0; \pm 1.6	large +ive*
VO ₂ submax (ml·kg ⁻¹ ·km ⁻¹)	197 \pm 9	185 \pm 10	-6.0; \pm 1.6	large +ive*
Relative intensity (%VO ₂ max)	74.7 \pm 7.6	69.5 \pm 7.9	-7.2; \pm 1.1	moderate +ive**
Minute ventilation (L·min ⁻¹)	82 \pm 12	76 \pm 13	-7.6; \pm 2.9	small +ive***
Heart rate (min ⁻¹)	163 \pm 11	158 \pm 11	-3.5; \pm 0.9	small +ive****
Respiratory exchange ratio	0.92 \pm 0.04	0.88 \pm 0.03	-3.5; \pm 1.8	moderate +ive**
Neuromuscular Measures				
Eccentric utilization ratio	1.02 \pm 0.05	1.08 \pm 0.06	5.8; \pm 1.9	moderate +ive***
Countermovement jump				
Peak force (N·kg ⁻¹)	66 \pm 18	64 \pm 21	-4; \pm 14	unclear
Peak power (W·kg ⁻¹)	51 \pm 16	54 \pm 19	5.8; \pm 7.2	small +ive*
Squat jump				
Peak force (N·kg ⁻¹)	54 \pm 14	59 \pm 22	6; \pm 20	unclear
Peak power (W·kg ⁻¹)	50 \pm 17	50 \pm 20	0.2; \pm 6.7	unclear
5-jump test				
Peak force (N·kg ⁻¹)	64 \pm 10	61 \pm 14	-5; \pm 13	unclear
Peak power (W·kg ⁻¹)	82 \pm 32	80 \pm 29	0; \pm 15	unclear
Stiffness (kN·m ⁻¹)	10.3 \pm 2.1	12.5 \pm 2.7	20.4; \pm 4.2	moderate +ive**

90%CL = 90% confidence limits. VO₂max = maximal aerobic capacity. +ive, -ive = substantial positive and negative changes with weighted-vest relative to control treatment.

^aInference about the magnitude of effect on peak speed was evaluated using a smallest important change of competitive distance running performance; effects on all other variables were evaluated by standardization.

*possibly, 25-75%; **likely, 75-95%; ***very likely, 95-99.5%; ****most (or extremely) likely, >99.5%

There were small to large improvements in all submaximal running measures (Table 9). When the pre-stride values were included in the analysis, the uncertainty in the treatment effect was greater and thus all values presented in Table 9 are from the post-only crossover analysis. Rating of perceived exertion during the second submaximal run was moderately higher (ES = 0.66) after the control warm-up condition and moderately lower (ES = 0.78) after the weighted-vest condition indicating at the beginning of the incremental performance test there was a moderate perception of easier running after weighted vest strides despite a small negative effect on perceived race readiness (Table 9). Individual and mean changes for running economy between conditions are presented in Figure 11.

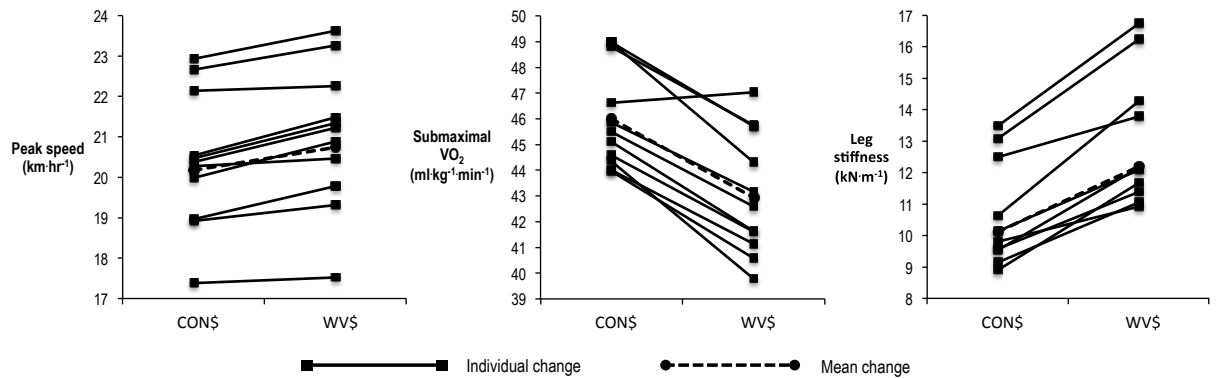


Figure 11: Individual values and mean for peak speed, submaximal VO_2 and leg stiffness in the control and weight-vest conditions.

Leg stiffness and EUR were moderately higher after weighted-vest strides compared with those of control strides ($ES = 0.76$ and 0.96 respectively). Individual and mean changes in leg stiffness between conditions are presented in Figure 11. Effects of the weighted vest condition on all other jump measures were unclear, except for peak power ($ES = 0.20$) (Table 9).

There was a very high correlation ($r = 0.88$, 90% confidence interval 0.66 to 0.96) between changes in performance and changes in leg stiffness. Changes in performance were also strongly related to changes in running economy ($r = 0.64$, 0.17 to 0.87) and minute ventilation ($r = 0.62$, 0.14 to 0.86). All other correlations were trivial or small. Using a linear regression model for the change scores in performance and change scores in respective mechanism variables, we determined that of the 2.9% improvement in performance, 3.4% ($\pm 90\%$ confidence limits, ± 1.1) was associated with changes in stiffness, while the change not associated with improvements in leg stiffness was -0.5% ($\pm 1.2\%$), indicating the change in performance independent of changes in stiffness following weighted-vest condition was actually a 0.5% impairment, although this result was unclear. The only other variable that had a clear association between its change scores and the change scores in performance was minute ventilation, which explained a 1.5% ($\pm 1.1\%$) change in performance, leaving a 1.4% ($\pm 1.3\%$) change independent of the changes in minute ventilation. Running economy explained a change of only 0.8% ($\pm 2.1\%$). While the effect of running economy on performance was unclear, we also investigated the joint effects of economy and stiffness on performance using a multiple linear regression model. The results from

this model showed that the independent effect attributable to running economy was only a trivial but unclear -0.1% ($\pm 1.2\%$), while the independent effect due to stiffness was unchanged (3.4% , $\pm 1.3\%$).

5.5 Discussion

The purpose of this study was to examine the acute effects of an added load to the strides that occur during a traditional warm-up preceding distance-running competition. The primary finding indicates beneficial effects on peak running speed performance and a range of neuromuscular and aerobic measures important to distance-running performance.

To our knowledge, this is the first study to demonstrate an improvement in running performance following a weighted-vest warm-up protocol in trained runners. The 2.9% improvement in performance should result in a similar change in running competition time (Hopkins et al., 2001). The effect is substantially greater than those in comparable studies. Ingham et al. (Ingham et al., 2013) reported a 1.2 s ($\sim 1\%$) improvement in 800-m running performance following a high-intensity warm-up compared to a traditional warm-up similar to that in this study. Hajoglou et al. (Hajoglou et al., 2005) reported little difference (a non-significant 0.2%) between 3-km cycling time-trial performance time following hard and traditional warm-up procedures. Similarly, Bishop et al. (Bishop et al., 2001) found no significant difference in peak power output during a 2-min kayak ergometer test following three different warm-up conditions.

In the current study performance was enhanced despite a small negative effect on perceived race readiness, which suggests the underlying mechanism of the enhancement was more than enough to overcome some sense of fatigue induced by the weighted-vest regimen. The mechanisms analysis supports this premise, in that we found some evidence (although unclear) of impairment in performance when changes in leg stiffness were adjusted to zero. The increase in leg stiffness itself explained all the improvement in performance. Acute changes in leg stiffness have also been reported in runners as a result of running on surfaces that differ in hardness (Ferris, Liang, & Farley, 1999) or chronically, following several weeks of strength and plyometric training (Burgess, Connick, Graham-Smith, & Pearson, 2007; Spurr et al., 2003).

The performance of skeletal muscle is affected by its contractile history; thus the explanation for the changes we observed following the warm-up with the weighted

vest is likely related to the phenomenon of post-activation potentiation (Sale, 2002). Muscle and tendon are two springs in series; an increase in stiffness therefore results in more potential energy stored in muscle and tendon, less muscle activation for running at a given speed, and a reduction in energy expenditure (Dalleau et al., 1998; Spurrs et al., 2003). Indeed, the weighted-vest condition elicited a 6.0% or $\sim 3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ reduction in VO_2 during submaximal running (Table 9, Figure 11). No researchers have reported improvements in running economy following priming exercise, though our difference in running economy are similar (Millet et al., 2002; Paavolainen, Hakkinen, et al., 1999) or better than (Guglielmo et al., 2009; Turner et al., 2003) those demonstrated in previous studies following a period (4 to 14 weeks) of resistance training in runners. Of most relevance, however, is the study by Rusko and Bosco (Rusko & Bosco, 1987), who reported a 2.2% improvement in running economy following a period (4 weeks) of training with a weighted vest ($\sim 10\%$ body mass). Acute (Hajoglou et al., 2005; Ingham et al., 2013) and chronic (Millet et al., 2002; Spurrs et al., 2003) exercise has also been shown to alter the metabolic and motor unit profiles of skeletal muscle as well as alter the pulmonary VO_2 kinetics (Jones, Wilkerson, Burnley, & Koppo, 2003), which has been shown to be advantageous for running performance (Spurrs et al., 2003).

The strong relationship between the change scores for performance and the change scores for leg stiffness is evidence for individual responses to the weighted-vest condition, such that greater increases in stiffness were associated with more enhancement of performance. Individual responses should be manifest as an increase in the standard deviation of change scores above the value observed in the absence of an intervention. We did not perform extra tests to estimate the standard deviation of change scores in the control condition, but reliability studies with subjects and protocols similar to ours provide an estimate of the standard error of measurement of $\sim 1.3\%$ (Hopkins et al., 2001), and the standard deviation of change scores would therefore be $\sim \sqrt{2} \times 1.3\% = \sim 1.8\%$. This value is actually *more* than the 1.6% we observed, but the uncertainty in this estimate (90% confidence limits 1.2 to 2.5%) allows for the possibility of substantial individual responses (Hopkins, 2007a). Their magnitude needs to be estimated in further research with repeated measurements in the control or weighted-vest conditions.

Despite the effect of running economy on performance being unclear, it is possible that economy is still a mediator linking the changes in stiffness to the changes in performance. After all, the improvement in running economy of 6.0%, other things being equal, would result in a $\sim 6\%$ enhancement in performance according to the

model of di Prampero et al. (di Prampero et al., 1993) However, the typical error of measurement of submaximal VO_2 in our laboratory was 1.8% (Barnes, Hopkins, et al., 2013b), which is probably considerably larger than the individual responses in submaximal VO_2 . Random error in a measure does not attenuate its mean change, but it does attenuate its slope as a predictor (Hopkins et al., 2009). Therefore the magnitude of the effect of running economy on performance was likely greater than estimated in our mechanisms analysis.

5.6 Conclusion

This is the first study to show that high-intensity running with an added load as part of an athlete's warm-up routine enhances subsequent performance in well-trained runners. The regression analysis suggests increases in leg stiffness following weighted vest strides are responsible for the improved performance. Future research should focus on optimizing the use of weighted vests in warm-up procedures to further enhance subsequent running performance.

5.7 Practical Implications

- The addition of a weighted vest to pre-competition strides improves peak-speed running performance.
- Running economy and lower-limb stiffness can be acutely augmented following priming exercise with an added load.
- Strides with a weighted vest offer a practical warm-up tool to enhance subsequent running performance.

5.8 Acknowledgements

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CHAPTER 6: EFFECTS OF DIFFERENT UPHILL INTERVAL-TRAINING PROGRAMS ON RUNNING ECONOMY AND PERFORMANCE

6.1 Abstract

Purpose Runners use uphill running as a movement-specific form of resistance training to enhance performance. However, the optimum parameters for prescribing intervals are unknown. We adopted a dose-response design to investigate the effects of various uphill interval-training programs on physiological and performance measures. **Methods** Twenty well-trained runners performed an incremental treadmill test to determine aerobic and biomechanical measures, a series of jumps on a force plate to determine neuromuscular measures, and a 5-km time-trial. Runners were then randomly assigned to one of five uphill interval-training programs. After 6 wk all tests were repeated. To identify the optimum training program for each measure, each runner's percent change was modeled as a quadratic function of the rank order of the intensity of training. Uncertainty in the optimum training and in the corresponding effect on the given measure was estimated as 90% confidence limits using bootstrapping. **Results** There was no clear optimum for time-trial performance, and the mean improvement over all intensities was 2.0% (confidence limits $\pm 0.6\%$). The highest intensity was clearly optimal for running economy (improvement of 2.4%, $\pm 1.4\%$) and for all neuromuscular measures, whereas other aerobic measures were optimal near the middle intensity. There were no consistent optima for biomechanical measures. **Conclusions** These findings support anecdotal reports for incorporating uphill interval training in the training programs of distance runners to improve physiological parameters relevant to running performance. Until more data are obtained, runners can assume that any form of high-intensity uphill interval training will benefit 5-km time-trial performance.

6.2 Introduction

Differences in sub-maximal oxygen uptake exist between athletes running at the same speeds, and these differences in "running economy" are a major factor explaining differences in running performance of endurance athletes (Conley & Krahenbuhl, 1980; Conley et al., 1984; Daniels & Daniels, 1992). Various strategies, such as altitude exposure (Saunders, Telford, et al., 2004), training in the heat (Saunders, Pyne, et al., 2004a), dynamic stretching (Craib et al., 1996), and high-intensity interval training (Conley & Krahenbuhl, 1980; Conley et al., 1984; Paton & Hopkins, 2004), have been proposed as methods to improve running economy via their effect on one or more of the metabolic, cardiorespiratory, neuromuscular and musculoskeletal systems. Most recent research has focused on the effects of supplementing endurance training with different forms of heavy-resistance or plyometric training to further improve running economy and running performance (Johnston et al., 1997; Millet et al., 2002; Paavolainen, Hakkinen, et al., 1999; Paavolainen, Nummela, & Rusko, 1999; Paton & Hopkins, 2004; Saunders et al., 2006; Spurrs et al., 2003; Storen et al., 2008; Turner et al., 2003). While coaches often utilize various forms of movement-specific resistance training in periodized training programs for distance runners, only anecdotal reports (Kurz et al., 2000; Midgley et al., 2007; Saunders, Pyne, et al., 2004a) and two research investigations (Ferley et al., 2012; Houston & Thomson, 1977) exist concerning the physiological responses and potential improvements in performance to such training. In one study, Ferley et al. (2012) compared effects of uphill interval-training and control (level-grade) interval training on various measures of performance in well-trained distance runners (Ferley et al., 2012). Although performance in both groups improved substantially, the only significant difference favored control training. In the other study, Houston and Thomson (1977) used a combination of uphill gradients and durations in addition to traditional resistance training in each training session (Houston & Thomson, 1977). Despite no changes in VO_{2max} , the authors found significant improvements in a time-to-exhaustion test as well as increased distance run in 60 and 90 s timed runs. The authors did not report running economy in either study.

In view of the uncertainty about the physiological effects of uphill training and other movement-specific form of resistance training on distance running performance, there is a clear need for more research in this area to identify optimal training (Paton & Hopkins, 2004). The conventional approach to investigating an optimum treatment is to perform a repeated-measures crossover study, with each subject receiving all treatments. However, this approach is often impractical in training studies, because

the long-lasting effects of training prevent subjects from receiving more than one type of training. To address this problem, Stepto et al. (1999) reported a novel and potentially more powerful dose-response design, in which individual cyclists received only a single form of training, and the optimum training "dose" was identified by modeling the effect of training as a polynomial function of the rank-ordered training intensity (Stepto et al., 1999). In the present study, we adopted the same modeling approach in an attempt to determine the most effective uphill interval-training protocol on running economy and performance in well-trained distance runners.

6.3 Methods

6.3.1 Design

We adopted a pre-post parallel groups design with measures conducted prior to and after a six-week intervention period. Subjects reported to the laboratory at least 2 hours post-prandial and having avoided strenuous exercise in the 24 hours preceding all test sessions. Prior to the intervention subjects performed baseline measures of the dependent variables on two occasions separated by three days. The first testing session included an incremental treadmill test to determine aerobic and biomechanical characteristics followed by a series of jumps to determine muscle power characteristics. The second testing session took place three days later and involved a 5-km outdoor time-trial. Four days after completing the final training session, each runner repeated the same set of tests in the same order as pre-intervention testing.

6.3.2 Subjects

Twenty distance runners (mean \pm SD) (age: 21 ± 4 , body mass: 65 ± 8 kg, height: 178 ± 9 cm) with an average 5-km race personal best time of 16.5 ± 1.2 min, average weekly training volume of 95 ± 25 km \cdot wk⁻¹ and training history of 6.3 ± 2.9 years, were randomly assigned to one of five uphill interval programs. The intervention training adherence rate for participants was 100%. As running volume was not manipulated in the current study, subjects in all groups continued with their normal running over the course of the study with the addition of the intervention substituting some of their normal running for interval training. Training logs for all subjects were monitored prior to and during the training. It was a requirement of the study that participants had not previously undertaken any structured interval training or resistance training in the previous six weeks. The study was approved by the institutional ethics committee and all participants provided informed written consent.

6.3.3 Treadmill Testing

All running tests were performed in a temperature controlled laboratory (19-

21°C; 65%rH) on a motorized treadmill (PowerJog, Birmingham, UK) set at a 1.0% gradient (Daniels & Daniels, 1992). After a standardized warm-up, subjects completed an incremental test to determine running economy involving repeated, progressively faster (increments of 1.0 km·h⁻¹) 4 min stages at four to six fixed running speeds ranging from 12 to 18 km·h⁻¹ until subjects were unable to sustain steady-state VO₂. A 90 s recovery period occurred between each stage for blood lactate sampling (Lactate Pro, Arkray, Japan) for later determination of the lactate threshold (D-max method) (Cheng et al., 1992). Expired gases were measured continuously using a metabolic cart (ParvoMedics TrueOne 2400, Salt Lake City, USA) for determination of VO₂, VCO₂, V_E, and RER. Heart rate was determined every 1 s (Polar RS800sd, Polar Electro, Finland). Running economy was defined as the mean VO₂ determined during the last minute of each running speed. Approximately 90 s after completion of the final submaximal running stage, VO_{2max} was determined during an incremental test to volitional exhaustion. Subjects commenced running at 1.0 km·h⁻¹ (1.5% gradient) below the final submaximal speed for 1 min. Thereafter, treadmill gradient was increased by 1% each minute until volitional exhaustion. The highest VO₂ over a 30 s period during the test was considered VO_{2max}. Changes in endurance performance were indicated by the peak running speed reached at the end of the incremental treadmill test. Because we used increases in gradient (rather than speed) in the latter part of the treadmill test, we calculated speed on the flat as $S = S_T + (S_T \times 0.045) \times i$; where S = peak speed in km·h⁻¹, S_T = treadmill speed in km·h⁻¹, and i = treadmill inclination in percent (Brooks et al., 1996).

6.3.4 Neuromuscular Measures on a Force Plate

After a 30 min passive recovery period, subjects performed a countermovement jump (CMJ) and squat jump (SJ) as previously described by McGuigan et al. (2006) and a five jump plyometric test (5J) described by Saunders et al. (2006) on an AccuPower force plate (Advanced Mechanical Technology Inc., Watertown, MA) to determine neuromuscular characteristics (Hopkins et al., 2001; McGuigan et al., 2006; Saunders et al., 2006). Each jumping test was performed twice. The following parameters were determined for each type of jump: peak force, time to peak force, peak power, maximum rate of force development (RFD), displacement, eccentric utilization ratio (EUR) and stiffness. Eccentric utilization ratio was calculated as the peak power ratio between performance on the CMJ compared to the SJ (McGuigan et al., 2006). Stiffness was estimated by dividing the peak force by the vertical displacement measured during the 5-jump test (Cavagna et al., 1988).

6.3.5 Running Performance

Three days after laboratory-based tests, each subject completed a 5-km self-paced time-trial on a 400-m outdoor tartan track. After the subject's typical self-chosen pre-competition warm-up (recorded and repeated post-intervention), subjects were instructed to run the distance "as fast as possible".

6.3.6 Training Interventions

Subjects performed two uphill interval-training sessions per week over a 6-wk period while maintaining their normal running training outside of the weekly interval training sessions. Specific details of the work:rest ratios, intensity and uphill gradient of the different training interventions are presented in Table 10. The work:rest ratios were not consistent with standard interval-training practice (Paton & Hopkins, 2004) but were designed to accommodate the practicalities of uphill interval training, when runners have to return to the bottom of a hill to start another repetition. The outcomes are therefore more likely to reflect what athletes should expect when they add uphill running to their training program.

Table 10: Details and progression of five different 6-week uphill interval-training programs (2 interval-training sessions per week).

	Group 1 (n = 3)	Group 2 (n = 5)	Group 3 (n = 5)	Group 4 (n = 4)	Group 5 (n = 3)
Gradient	18%	15%	10%	7%	4%
%HR _{max}	100%	100%	98-100%	93-97%	88-92%
Velocity (vVO _{2max})	120%	110%	100%	90%	80%
Work:Rest ratio	1:6	1:3	1:2	1:1.5	1:1
6 wk workout progression					
Week 1	12× 8 s	8× 30 s	5× 2 min	4× 4 min	2× 10 min
Week 2	16× 10 s	10× 35 s	5× 2.5	4× 5 min	2× 15 min
Week 3	20× 10 s	12× 40 s	7× 2 min	5× 4.5	1× 20 + 1× 15
Week 4	20× 12 s	12× 45 s	7× 2.5	5× 5 min	2× 20 min
Week 5	24× 10 s	16× 40 s	9× 2 min	6× 5 min	3× 15 min
Week 6	24× 12 s	16× 45 s	9× 2.5	7× 5 min	2× 25 min

6.3.7 Statistical Analyses

We performed simulations to determine the sample size that would give an acceptable confidence interval for optimum performance predicted with a quadratic dose-response model. In these simulations, the training protocol was a variable that ranged from 1 for the highest intensity and shortest duration through 5 for the lowest intensity and longest duration. Data were generated that had no real polynomial

effects, because data without effects need the largest sample sizes to define the magnitude of the effects with acceptable precision. With 20 subjects, an error of measurement for an individual's running economy of 2%, and a quadratic model, the 90% confidence interval was acceptable.

All performance and other outcome measures were analyzed as percentage changes via the transformation $\log [(post\ measurement)/(pre\ measurement)]$ (Hopkins, Hawley, & Burke, 1999). The transformed data were modeled as a quadratic function of the rank-ordered intensity of the training protocols to determine the optimum training dose and the value of the change in the outcome measure at this dose (Hopkins, 2006). The standard error of the estimate from the model divided by $\sqrt{2}$ provided an estimate of the error of measurement for the outcome measure under conditions of the experiment (after adjustment for the dose-response relationship). Confidence intervals for the measures derived from the quadratic model were generated by bootstrapping using a customized Excel spreadsheet (Hopkins, 2012). For the value of the change in the outcome measure at the optimum dose, bootstrapping also provided estimates of the probabilities that the true change was greater or less than the smallest important beneficial and harmful change.

To make conclusions about the true effects of training on performance and other outcome measures, we used the clinical form of magnitude-based inference: unclear effects were those with the possibility (>25% chance) of benefit but an unacceptable risk of harm (odds ratio of benefit to harm <67) (Hopkins et al., 2009). All other effects were clear and reported with a qualitative probability for the true magnitude using the following scale: 25-74%, possibly; 75-94%, likely; $\geq 95\%$, very likely. This approach to inference requires an estimate for smallest important change in each outcome measure. The smallest enhancement of performance that has a substantial effect on an athlete's chance of improvement is 0.3 of the typical within-athlete variation of performance between competitions (Hopkins et al., 1999). The variability of performance of high-level competitive distance runners (3-10 km) is 1.1% (Hopkins, 2005); consequently a smallest important change of 0.3% was used for measures of performance.

To analyze potential mechanisms underlying the effect of training on performance, changes in performance were plotted against changes in physiological and other measures and the scatterplots inspected for any linear trend. A clear linear trend in the graph would have allowed for estimation of the smallest important change in the mechanism variable as the change that tracked the smallest important change in performance. However, there were no such clear linear relationships, presumably

because random error of measurement masked any relationship between real individual differences in changes in performance and the mechanism variable. A different approach to estimating smallest changes was therefore adopted. The enhancement in performance turned out to be practically constant across the range of training intensities (~2%). Therefore, to estimate the smallest important change in each mechanism variable, we assumed that the tracking of changes in the means of the mechanism and performance variables reflected the underlying relationship in the individual change scores. The smallest important change in the mechanism variable was therefore $0.3\% \times (\Delta \text{ mechanism})/(\Delta \text{ performance})$, where Δ is the change in the mean; for example, the smallest important change in VO_2max was calculated as $0.3\% \times (4.1/2.0) = 0.62\%$.

6.4 Results

Figure 12 shows the percentage change and quadratic trends for identifying optimum training intensity with bootstrapped confidence limits for performance and selected other measures for the individual subjects in the rank order intensity of each group after the uphill interval-training intervention. Table 11 shows baseline values of outcome measures and statistics from the bootstrap analyses for inferences about the optimum intensity and duration of interval training and about the effects on the outcome measures at the optimum. A well-defined outcome for the effect of dose of training on outcome measures present in Table 11 was shown if the proportion of successful bootstrap simulations (bootstrap success rate) was $\geq 90\%$ and there was a reasonable confidence interval associated with the dose (Group) or the confidence interval is limited to one of the dose-extremes (i.e. 1, 1 or 5, 5). Errors of measurement derived from the modeling are also shown in Table 11 and allow assessment of the precision of the measures in comparison with those in reliability studies (see Discussion).

Data for the 5-km time-trial showed a weak quadratic trend (Figure 12). The modeling predicted an optimum near the middle of the range of training intensity and duration (Group = 2.3, as shown in Table 11) and a likely beneficial effect on performance (-2.0%). However, the bootstrap success rate (57%) represents inconsistency in the curvature of the bootstrapped quadratics; that is, only 57% predicted a minimum in performance time, and the resulting confidence interval for the optimum treatment extended to both extremes of the treatment range (1 to 5). Changes in peak speed showed similar results.

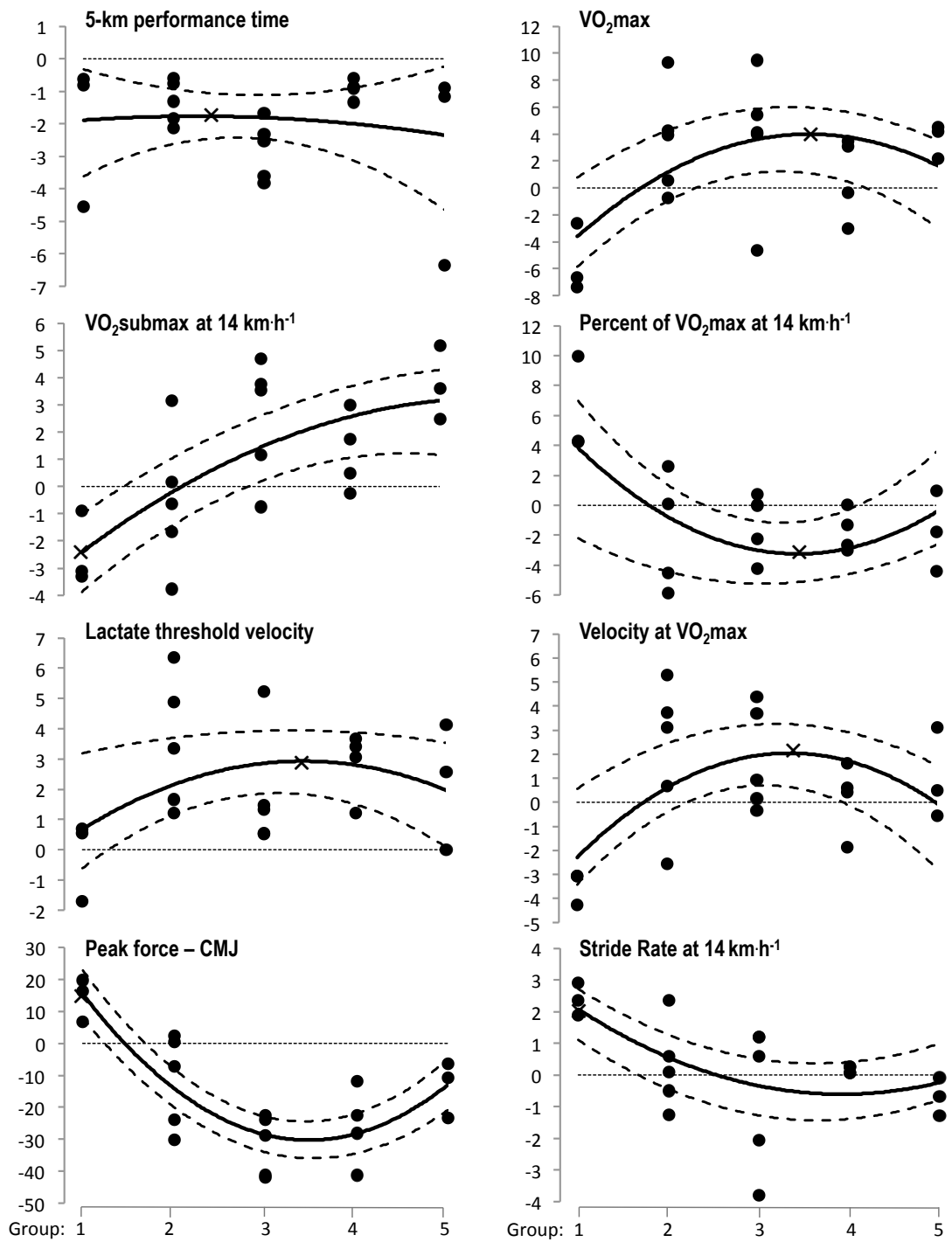


Figure 12: Percentage change in performance and selected physiological measures after the five uphill interval-training programs. • represents individual changes in runners. Solid curved line represents mean from quadratic modeling and dashed curved lines are the associated confidence limits generated from bootstrapping. × represents the predicted group optimum.

There was a strong trend towards Groups 3 to 4 having the optimal training parameters to improve all aerobic measures besides running economy (Figure 12, Table 11). There were well-defined outcomes for the effects on aerobic measures obtained during the incremental treadmill test (bootstrap success rate $\geq 90\%$) indicating consistency in predicting a maximum at the turning point). Most of the aerobic measures had reasonably narrow confidence limits for the training intensity (i.e. Group) and the two running economy measures had an optimum precisely defined at the highest intensity (Group 1) (Table 11). The effects at the optima were also clear. Improvements in all aerobic measures except running economy were made across Groups 2 through 5 with the optima occurring near the middle of this range, whereas Group 1 showed a negative effect in most aerobic measures. However, the reverse phenomena occurred for running economy where the effects only showed improvements in Group 1 (Figure 12).

Improvements in biomechanical measures (Figure 12 – Stride rate, Table 11) favored Groups 1 to 3 training (Table 11). Bootstrap success rate was variable from measure to measure. Accordingly, the confidence limits for the training intensity and effects reflect this with narrow confidence limits around measures with well-defined outcomes (bootstrap success rate $\geq 90\%$) and wide confidence limits around those without well-defined outcomes (low bootstrap success rate, Table 11). All improvements in muscle power measures favored Group 1 training (Table 11) and the changes across all groups were similar to that of CMJ peak force shown in Figure 12. There was a high bootstrap success rate for the eccentric utilization ratio, stiffness, peak force, time to peak force, and maximum rate of force development of all three jumps ($\geq 85\%$) and low in the peak power measurements of all three jumps ($\leq 36\%$). Where confidence limits were narrow for the optimal training group so were the confidence limits for the effects at the optima. Inferences about the effects on performance and other outcome measures showed likely or very likely benefit at the predicted optima.

Table 11: Outcome measures at baseline and statistics from the bootstrap analyses for inferences about the effects at the predicted group optimum.

	Baseline values (mean \pm SD)	Error ^a (%)	Bootstrap success rate (%)	Predicted optimum group and corresponding effect (with 90%CL)	
				Group ^b	Effect (%)
Running Performance					
5-km performance time	17.0 \pm 1.3 min	1.2	57	2.3 (1, 5)	-2.0 (-2.5, -1.3)*
Peak speed	21.4 \pm 1.9 km·h ⁻¹	1.2	54	3.1 (1, 5)	2.0 (1.8, 3.7)**
Aerobic Measures					
VO ₂ max	63.9 \pm 5.9 ml·kg ⁻¹ ·min ⁻¹	3.0	96	3.6 (2.9, 4.6)	4.1 (2.2, 6.6)**
vVO ₂ max	18.7 \pm 1.5 km·h ⁻¹	1.7	98	3.4 (2.7, 4.1)	2.0 (1.0, 3.4)**
Lactate threshold velocity	15.9 \pm 1.6 km·h ⁻¹	1.4	91	3.4 (2.2, 5)	2.9 (2.3, 4.2)**
VO ₂ submax @ 14 km·h ⁻¹	53.7 \pm 3.0 ml·kg ⁻¹ ·min ⁻¹	1.5	90	1 (1, 1)	-2.4 (-3.9, -1.0)**
VO ₂ submax @ 14 km·h ⁻¹	201 \pm 11 ml·kg ⁻¹ ·km ⁻¹	1.5	90	1 (1, 1)	-2.4 (-3.9, -1.0)**
% of VO ₂ max @ 14 km·h ⁻¹	84.4 \pm 7.6 %VO ₂ max	3.0	96	3.5 (1.9, 4.4)	-3.2 (-6.2, -1.9)*
Biomechanical Measures					
Stride rate	87.8 \pm 4.5 strides·min ⁻¹	1.0	93	1 (1, 1)	2.1 (0.9, 2.7)**
Stride length	3.03 \pm 0.21 m	1.7	64	2.3 (1, 5)	0.4 (0.0, 2.3)*
Contact time	0.22 \pm 0.02 s	3.0	88	3.1 (1, 5)	-5.2 (-8.0, -3.9)**
Flight time	0.12 \pm 0.02 s	6.1	91	3.4 (2.8, 5)	10 (6, 18)**
Neuromuscular Measures					
Eccentric Utilization Ratio	1.03 \pm 0.06	2.2	98	1 (1, 1)	12 (8, 16)**
Stiffness	11.0 \pm 2.5 kN·m ⁻¹	3.5	85	1 (1, 1.8)	25 (8, 39)**
Countermovement Jump					
Peak force	63 \pm 19 N·kg ⁻¹	7.7	100	1 (1, 1)	15 (9, 24)**
Time to peak force	1.82 \pm 0.47 s	13	92	1 (1, 3.2)	7.2 (-2, 29)*
Peak power	42.6 \pm 6.3 W·kg ⁻¹	7.5	36	1 (1, 5)	2.6 (-4.1, 8.8)*
Maximum RFD	101 \pm 50 kN·s ⁻¹	20	100	1 (1, 5)	29 (6, 52)**
Squat Jump					
Peak force	58 \pm 14 N·kg ⁻¹	7.7	100	1 (1, 1)	12 (7, 22)**
Time to peak force	2.04 \pm 0.69 s	12	92	1 (1, 1)	-7.5 (-16, 4)*
Peak power	43.9 \pm 6.0 W·kg ⁻¹	7.9	12	1 (1, 5)	-3.9 (-11, 2)?
Maximum RFD	94 \pm 34 kN·s ⁻¹	12	99	1 (1, 1)	19 (13, 29)**
5-Jump Test					
Peak force	64.5 \pm 5.4 N·kg ⁻¹	7.7	96	1 (1, 1)	8.4 (-1, 13)**
Time to peak force	2.75 \pm 0.71 s	15	99	1 (1, 1)	-22 (-33, 0)**
Peak power	69 \pm 13 W·kg ⁻¹	7.6	29	1 (1, 5)	4.5 (-2, 10)*
Maximum RFD	105 \pm 47 kN·s ⁻¹	20	97	1 (1, 3.6)	21 (-5, 48)*

CL = confidence limits. VO₂max = maximal aerobic capacity. vVO₂max = velocity at VO₂max. RE = running economy. %VO₂max = percent of VO₂max. RFD = rate of force development.

^aError of measurement derived from the bootstrap analysis (which adjusts for any quadratic effect of group and thereby provides an estimate of error approximating the typical error in a 6-wk reliability study without an intervention).

^bGroup range = 1 to 5 (Table 10). For example, 2.3 indicates that the optimum training fell between Groups 2 and 3, and therefore had an intensity of 100-110% (of vVO₂max), a duration of 30-120 s and a gradient of 10-15%.

*likely beneficial; **very likely beneficial; ?unclear.

1 **6.5 Discussion**

2 In the present study we used a novel design and analysis approach, previously
3 adopted by Stepto et al. (1999), to determine the effects of different types of uphill
4 interval-training programs on running economy and performance in trained distance
5 runners (Stepto et al., 1999). A major finding was that no specific uphill-training
6 approach was associated with greater gains in 5-km time trial performance, but that
7 curvilinear relationships existed between a continuum of hill training approaches on
8 several performance-related physiological variables, including running economy
9 (Figure 12). Running performance improved across the range of training intensities
10 without a strong curvilinear relationship between uphill training characteristics and a
11 subsequent change in 5-km time-trial performance or peak running speed. The 2%
12 improvement in running performance was similar to other studies demonstrating
13 concurrent improvements in running economy and performance while employing
14 various modes of resistance training (Paavolainen, Hakkinen, et al., 1999; Spurrs et al.,
15 2003). Ferley et al. (2012) also demonstrated a ~2% improvement in estimated time-
16 trial performance (Hopkins et al., 2001) following 6 wk of uphill-interval training similar
17 to Group 2 training in the present study (Ferley et al., 2012).

18 The error of measurement derived from the bootstrap analysis for 5-km time
19 trial performance was 1.2%, which is comparable to other studies employing true
20 reliability studies with well-trained distance runners (Hopkins, 2005; Hopkins &
21 Hewson, 2001; Laursen, Francis, Abbiss, Newton, & Nosaka, 2007); suggesting to us
22 there is limited evidence for individual responses to training. The correlations between
23 percent changes in 5-km performance and percent changes in each of the aerobic,
24 biomechanical, neuromuscular, and peak speed measures were unclear. A lack of
25 clear correlations provides additional support for no individual responses to explain.
26 However, because every participant demonstrated some sort of improvement in 5-km
27 time-trial performance it can be suggested that running performance enhancements
28 can be made as a result of changes in a variety of mechanistic variables caused by
29 varying the uphill running loading parameters.

30 With regards to effect of uphill interval-training on improvements on selected
31 aerobic, neuromuscular, and biomechanical measures, the various 6 wk uphill interval-
32 training programs resulted in curvilinear trends, often with an identified optimum (Figure
33 12). There was a well-defined outcome for the effect of dose of training on all aerobic
34 measures and most biomechanical and neuromuscular measures. A larger sample
35 size would be needed to establish clear optima for the other outcomes. Except for

1 improvements in running economy, our model predicted optimal enhancements after
2 work bouts associated with an intensity between Groups 3 and 4 training (Table 10).
3 The enhancements observed for aerobic measures (Table 11) besides running
4 economy is perhaps unsurprising since the intensity of these work bouts occurred at or
5 near $VO_2\text{max}$ which is in accord with the principle of specificity. It is highly likely these
6 changes were a result of the additional uphill interval training because all subjects were
7 undertaking similar running training outside of the present study ($95 \pm 25 \text{ km}\cdot\text{wk}^{-1}$). In
8 contrast, the two studies utilizing uphill interval-training reported no change (Houston &
9 Thomson, 1977) or a decrement in $VO_2\text{max}$ (Ferley et al., 2012).

10 We observed that training at the highest intensities (Group 1 and 2) was
11 associated with the greatest improvements in running economy and neuromuscular
12 characteristics as well as increased stride rate. Ours is the first study to demonstrate
13 that a regimen of high-intensity uphill interval training improves running economy. The
14 magnitude of the improvement (2.4%) is consistent with previous studies reporting
15 positive effects of traditional resistance training or plyometric training on running
16 economy in runners with a wide range of ability (Johnston et al., 1997; Millet et al.,
17 2002; Paavolainen, Hakkinen, et al., 1999; Paavolainen, Nummela, & Rusko, 1999;
18 Saunders et al., 2006; Spurrs et al., 2003; Storen et al., 2008; Turner et al., 2003) as
19 well as anecdotal reports of the benefits of uphill sprinting (Kurz et al., 2000; Midgley et
20 al., 2007; Saunders, Pyne, et al., 2004a). The observed improvement in running
21 economy was accompanied by similar reduction in $VO_2\text{max}$ and consequently an
22 increase in $\%VO_2\text{max}$ in Group 1 (Figure 12). This is not surprising given the training
23 imposed on athletes in Group 1 (Table 10) would be unlikely to augment $VO_2\text{max}$
24 anyway. It is known a positive relationship exists between maximal and submaximal
25 VO_2 indicating that athletes with higher aerobic demands of running (i.e. poorer running
26 economy) tend to have higher $VO_2\text{max}$ values which may also explain the positive shift
27 in running economy and negative shift in $VO_2\text{max}$ (Daniels, 1985; Morgan & Daniels,
28 1994; Noakes, 1988; Pate et al., 1992). The theoretical underpinnings of this
29 observation have yet to be fully elucidated, but may relate to various neuromuscular
30 and/or biomechanical characteristics. It should be noted that regardless of the
31 changes in running economy, $VO_2\text{max}$ and $\%VO_2\text{max}$, Group 1 training still resulted in
32 an ~2% improvement in 5-km run performance (Figure 12).

33 The fact that the greatest improvements in neuromuscular measures also
34 occurred with the highest intensity of training (Table 11) may support the
35 aforementioned premise that the enhancement of running economy was due to a range
36 of mechanisms relating to recruitment and coordination of muscle fibers, efficiency of

1 muscle power development, as well as better use of the muscle-tendon units stored
2 elastic energy. An indirect measure of this storage and return of muscular energy is
3 the EUR in which we found 12% improvements in Group 1 training (Table 11). Another
4 key function of the active skeletal musculature during running is to regulate the
5 stiffness of the muscle-tendon apparatus to maximize the exploitation of elastic energy,
6 which improves running economy (Cavagna et al., 1988). Like other neuromuscular
7 characteristics, leg stiffness measured in this study showed the greatest improvements
8 at the highest training intensity (Table 11). The error of measurement for
9 neuromuscular measures in Table 11 adds some uncertainty to the true relationship
10 between training dose and effect, but is not unreasonable given the measured-error is
11 population specific and is still comparable to other reliability studies (Cormack, Newton,
12 McGuigan, & Doyle, 2008). The improvements in neuromuscular measures are also in
13 agreement with a number of other studies using various forms of explosive resistance
14 training or plyometric type of activities such as hopping, jumping and bounding as ways
15 to directly or indirectly potentiate neuromuscular adaptations (Paavolainen, Hakkinen,
16 et al., 1999; Paavolainen, Nummela, & Rusko, 1999; Saunders et al., 2006; Spurr et
17 al., 2003; Turner et al., 2003).

18 Finally, another plausible explanation for improved running economy after high
19 intensity uphill interval training is training-induced alteration in stride rate, which was
20 also greatest at the highest intensity of training (Figure 12, Table 11). Paavolainen et
21 al. (1999) observed similar changes in stride characteristics in response to nine weeks
22 of explosive-strength training in well-trained endurance runners along with concurrent
23 ~8% improvement in running economy (Paavolainen, Hakkinen, et al., 1999). The
24 changes in biomechanical measures may themselves be explained at least partly by
25 changes in neuromuscular characteristics.

26 **6.6 Practical Applications and Conclusion**

27 Our findings provide support for incorporating uphill interval running in the
28 training programs of distance runners to improve various physiological, biomechanical
29 and neuromuscular parameters relevant to running performance. Different uphill
30 training approaches appear to induce specific physiological and mechanical
31 adaptations, which suggests that hill training should be carefully matched to the
32 strengths and weaknesses of the athlete, the underlying demands of the event and the
33 training or competitive focus. Until more data are obtained, runners can assume that
34 performance enhancements can be made as a result of changes in a variety of
35 mechanistic variables caused by varying the uphill running loading parameters since
36 every participant demonstrated some sort of improvement in 5-km time-trial

1 performance. Further studies are required to establish whether improvements derived
2 from uphill interval training can be established through variations in the frequency,
3 duration, volume and periodization of training.
4

1 **CHAPTER 7: EFFECTS OF RESISTANCE TRAINING ON RUNNING ECONOMY**
2 **AND CROSS-COUNTRY PERFORMANCE**

3

4 **7.1 Abstract**

5 **Purpose** Heavy-resistance training and plyometric training offer distinct
6 physiological and neuromuscular adaptations that could enhance running economy and
7 consequently distance-running performance. To date no studies have examined the
8 effect of combining the two modes of training on running economy or performance.
9 **Methods** Fifty collegiate male and female cross-country runners performed a 5-km
10 time-trial and a series of laboratory-based tests to determine aerobic, anthropometric,
11 biomechanical and neuromuscular characteristics. Thereafter, each athlete
12 participated in a season of 6-8 collegiate cross-country races over 13 weeks. After the
13 first four weeks, athletes were randomly assigned to either heavy-resistance or
14 plyometric plus heavy-resistance training. Five days after completing their final
15 competition, runners repeated the same set of laboratory tests. We also estimated
16 effects of the intervention on competition performance throughout the season using
17 athletes of other teams as controls. **Results** Heavy-resistance training produced
18 small-moderate improvements in peak speed, running economy and neuromuscular
19 characteristics relative to plyometric resistance training, whereas changes in
20 biomechanical measures favored plyometric resistance training. Males made less
21 gains than females in most tests. Both treatments had possibly harmful effects on
22 competition times in males (mean 0.5%; 90% confidence limits $\pm 1.2\%$), but there may
23 have been benefit for some individuals. Both treatments were likely beneficial for all
24 females (-1.2% ; $\pm 1.3\%$), but heavy-resistance was possibly better than plyometric
25 resistance training. **Conclusion** The changes in laboratory-based parameters related
26 to distance-running performance were consistent with the changes in competition times
27 for females but only partly for males. Our data indicate that females should include
28 heavy-resistance training in their programs, but males should be cautious about using it
29 in season until more research establishes whether certain males are positive or
30 negative responders.

31

1 **7.2 Introduction**

2 Trained runners have superior running economy compared to lesser-trained or
3 untrained runners (Daniels, 1974b; Daniels & Daniels, 1992; Jones, 1998; Lucia et al.,
4 2006; Lucia et al., 2008; Saltin et al., 1995), indicating positive adaptations in response
5 to training programs. Recent research has shown running economy to improve in
6 runners using traditional strength training or explosive, plyometric training (Johnston et
7 al., 1997; Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006). It is well
8 documented that initial performance gains following traditional heavy resistance
9 training are a result of predominantly neuromuscular rather than within muscle
10 adaptations (i.e. hypertrophy) (Kraemer et al., 1996). These adaptations may include
11 increases in strength, increased motor unit recruitment, improved mechanical efficiency
12 and muscle coordination (Kraemer et al., 1996; Kyrolainen et al., 2001; Sale, 1988). A
13 key component to running economy is the ability to store and recover elastic energy
14 from the eccentric contraction (Cavanagh & Kram, 1985b). Plyometric training is a
15 form of strength training that aims to enhance the ability of the muscles to generate
16 power through the SSC by use of explosive activities such as jumping, hopping and
17 bounding (Turner et al., 2003). Several studies have indicated improvement in running
18 economy from concomitant plyometric and endurance training (Paavolainen, Hakkinen,
19 et al., 1999; Spurrs et al., 2003; Turner et al., 2003). Proposed explanations for the
20 improvement include increased lower body muscle-tendon stiffness, degree of neural
21 input to the muscle, enhanced muscle power development and elastic return, and
22 improved motor unit synchronization (Paavolainen, Hakkinen, et al., 1999;
23 Paavolainen, Nummela, Rusko, et al., 1999; Spurrs et al., 2003). Conversely or in
24 concert improvements from either form of resistance training may enhance running
25 mechanics. Improved biomechanical efficiency and improved leg muscle co-activation
26 and coordination may allow for a reduction in relative workload (Hoff et al., 1999;
27 Johnston et al., 1997; Kyrolainen et al., 2001). The combination of improved running
28 mechanics, neuromuscular efficiency, and strength may result in a decrease in oxygen
29 consumption, thereby improving running economy and ultimately performance. Indeed
30 the combination of heavy-resistance training and plyometric training may facilitate
31 additional improvements in running economy via accumulation of adaptations
32 previously observed when either type of training is performed alone.

33 There is a strong association between running economy and distance running
34 performance (Barnes, Hopkins, et al., 2013b; Conley & Krahenbuhl, 1980; Daniels,
35 1985; Daniels & Daniels, 1992). Accordingly, it is likely that any improvement in
36 running economy as a result of training will be associated with improved distance
37 running performance. A review of the literature, however, produced no studies

1 examining the effects of a resistance-training intervention on running economy or
2 performance during the competition phase of a running season, likely because coaches
3 are often unwilling to do time trials or other performance tests that would interfere with
4 preparations for actual competitions. Fittingly, Vandembogaerde, Hopkins and Pyne
5 (Vandembogaerde et al., 2012) recently reported a novel design for investigating the
6 effects of an intervention on competition performance, in which changes in
7 performance between competitions before and after an intervention with a squad of
8 athletes were compared with changes in performance in other squads over the same
9 time frame. To enhance the ecological validity of the present study and as the primary
10 purpose of the investigation, we adopted this research design in an attempt to compare
11 the effects of heavy resistance training versus the combination of heavy resistance-
12 and plyometric-training on performance during the competitive phase of a men's and
13 women's collegiate cross-country running season.

14 **7.3 Methods**

15 Prior to the competitive season, an entire collegiate cross-country team
16 performed a 5-km time trial and a series of laboratory tests including an incremental
17 treadmill test to determine aerobic and biomechanical characteristics and a series of
18 maximal jumps to determine muscle power characteristics. Thereafter, each athlete
19 participated in a series of competitive collegiate cross-country races over a 13-week
20 period (Figure 13). Approximately one-third of the way through the competitive season,
21 each athlete was prescribed one of two resistance training programs; either Group 1:
22 traditional heavy resistance training (HRT) or Group 2: plyometric and heavy resistance
23 training (PRT). We then estimated the effects of the intervention on performance in a
24 design equivalent to a parallel-groups controlled trial with athletes of other teams being
25 the control group. Five days after completing the final competition of the season, each
26 runner repeated the same set of laboratory tests. The study was approved by the
27 Auckland University of Technology Ethics Committee; Auckland, New Zealand, and the
28 Hope College Human Subjects Review Board; Holland, Michigan, USA. All participants
29 provided informed written consent to participate.

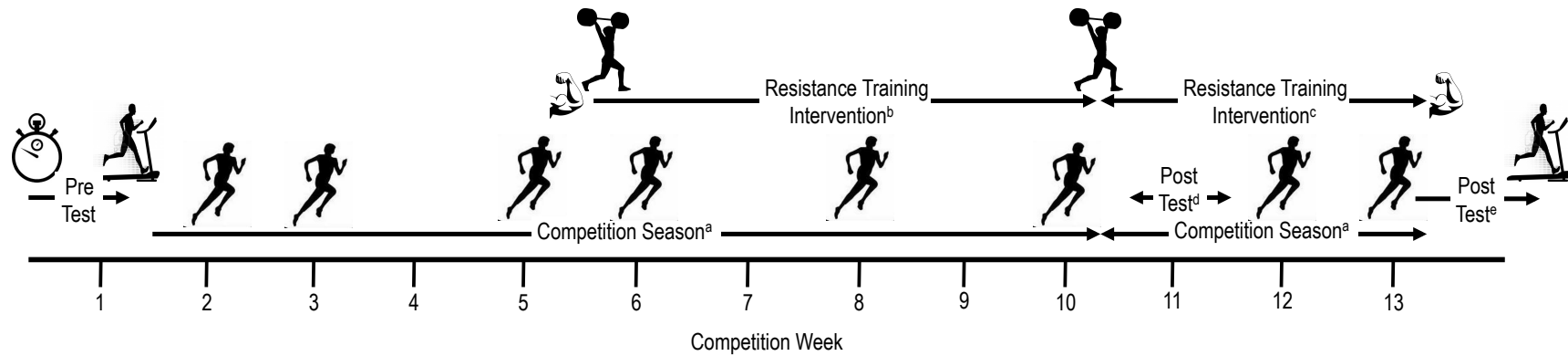


Figure 13: Schematic representation of experimental design, indicating pre- and post-testing, competition and intervention periods.

^aMen did not race in weeks 3 and 13 competitions.

^bResistance training for all runners.

^cResistance training for top (fastest 7) male and female runners competing in weeks 12 and/or 13 championship competitions.

^dPost testing for runners who did not qualify for weeks 12 or 13 championship competitions.

^ePost testing for runners competing in weeks 12 and/or 13 championship competitions.

7.3.1 Subjects

Fifty collegiate cross-country runners (men = 28, women = 22) participated in the study (Table 12). Subjects all competed at the Division 3 National Collegiate Athletics Association (NCAA) level with both teams being ranked nationally. Eight runners failed to complete the prescribed training program and were eliminated from the study. The main reasons were; inability to complete intervention or testing procedures (n = 3), dropout (n = 1) and injury (n = 4). The final sample size for analysis was 42 (Men: n = 23, HRT = 13, PRT = 10; Women: n = 19, HRT = 9, PRT = 10). All athletes trained and competed together 6 days wk^{-1} under the guidance of the same coach and performed similar workouts to their teammates over the duration of the season. Training logs for all subjects were collected prior to and after the competitive season, and the primary author observed each training session and competition. During week 1 each subject completed a 5-km time trial on a flat 1250-m grass loop (Figure 13). All subjects were instructed to run the distance “as fast as possible” to get a baseline measure of fitness and prescribe subsequent training intensities under the guidance of their coach (Table 12). Gender and 5-km time was used to sequentially allocate subjects to either HRT or PRT (Hopkins, 2010). Participants had not previously undertaken any structured resistance or plyometric training in the previous ten weeks prior to the competitive season.

Table 12: Subject and training characteristics with effects and inferences about differences between groups.

		Group 1 - PRT (mean \pm SD)	Group 2 - HRT (mean \pm SD)	Qualitative interpretation of difference in means (Cohen ES)^a
	Men (n = 23) Women (n = 19)	(n = 10M, 10W)	(n = 13M, 9W)	
Age (y)	M	20.7 \pm 1.2	19.6 \pm 1.1	moderate (0.94)
	F	20.5 \pm 1.2	19.7 \pm 1.1	moderate (0.72)
Body mass (kg)	M	68.7 \pm 8.8	65.4 \pm 5.6	small (0.42)
	F	53.4 \pm 5.8	55.9 \pm 5.9	small (0.40)
Body fat (%)	M	6.8 \pm 2.3	7.2 \pm 2.1	trivial (0.14)
	F	16.1 \pm 2.2	16.6 \pm 3.6	trivial (0.18)
Training history (y)	M	6.5 \pm 1.8	5.9 \pm 0.8	small (0.40)
	F	6.9 \pm 1.3	6.0 \pm 1.3	moderate (0.67)
Training volume ($\text{km}\cdot\text{wk}^{-1}$)	M	93.7 \pm 15.0	91.9 \pm 12.1	trivial (0.13)
	F	73.6 \pm 13.8	72.3 \pm 13.3	trivial (0.10)
Training intensity $\geq 80\%$ VO_2max (%) ^b	M	17.4 \pm 2.3	17.2 \pm 2.8	trivial (0.07)
	F	20.9 \pm 4.1	20.5 \pm 4.2	trivial (0.08)
5-km time trial (min)	M	16.8 \pm 0.9	16.7 \pm 0.7	trivial (0.14)
	F	20.1 \pm 0.9	20.2 \pm 1.3	trivial (0.07)

M = male. F = female. HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training. ES = effect size.

^a<0.20 trivial; ≥ 0.20 small; ≥ 0.60 moderate; ≥ 1.2 large

^bPercent of weekly training volume that occurred at $\geq 80\%$ VO_2max .

7.3.2 Testing Procedures

7.3.2.1 Body Composition

On arrival to the laboratory, subjects were weighed (BOD POD CosMed USA, Inc., Chicago, USA) in their running shorts to the nearest 0.1kg and their body composition was determined using air-displacement plethysmography (BOD POD GS).

7.3.2.2 Treadmill Testing

All running tests were performed in a temperature-controlled laboratory (19-21DegC; 65%rH) on a motorized treadmill (TrackMaster TMX425 Full Vision Inc., Newton, USA) set at a 1.0% gradient (Daniels, 1998). Before each test, subjects warmed up at a self-selected exercise intensity for five minutes. The amount of work performed during the warm-up was recorded and repeated during subsequent exercise tests. After the warm-up, the subjects completed an incremental treadmill test to determine running economy involving repeated, progressively faster (increments of 1.0 km·h⁻¹) 4 min stages at fixed running speeds (12 to 18 km·h⁻¹ for men and 11 to 17 km·h⁻¹ for women) until subjects were clearly no longer able to sustain a steady-state VO₂ (i.e. a slow component was evident), as determined visually from real-time plots of VO₂. From further post-test inspections of VO₂ data, the maximum velocity at which steady-state oxygen consumption was achieved across the range of subjects was determined (14 km·h⁻¹) and used thereafter as our primary measure of running economy. A 90 s recovery period occurred between each stage. Expired gases were measured continuously using a metabolic cart (ParvoMedics TrueOne 2400, Salt Lake City, USA) for determination of VO₂, carbon dioxide production, minute ventilation and respiratory exchange ratio. Running economy was defined as the mean VO₂ determined during the last minute of each running stage. In our laboratory, the typical error of measurement (Hopkins, 2000) of submaximal VO₂ was 1.8%. Approximately 90 s after completion of the final submaximal running stage, VO₂max was determined during an incremental test to volitional exhaustion. Subjects commenced running at 1.0 km·h⁻¹ (1.0% gradient) below the final submaximal speed for 1 min. Thereafter, treadmill gradient was increased by 1% each minute until volitional exhaustion. The highest VO₂ over a 30 s period during the test was considered VO₂max. Changes in endurance performance were indicated by the peak running speed reached at the end of the incremental treadmill test. Because we used increases in gradient (rather than speed) in the latter part of the treadmill test, we calculated equivalent speed on the flat as $S = S_T + (S_T \times 0.045) \times i$; where S = peak speed in km·h⁻¹, S_T = treadmill speed in

km·h⁻¹, and *i* = treadmill inclination in percent (Brooks et al., 1996). Heart rate was determined every 1 s throughout the incremental test using short-range telemetry (Polar RS800sd, Polar Electro, Finland).

7.3.2.3 Force Plate Measures

Following the incremental test, after a 30 min passive recovery period, subjects performed a 5-jump plyometric test involving five continuous straight-leg jumps on an AccuPower force plate (Advanced Mechanical Technology Inc., Watertown, MA) to determine neuromuscular characteristics. Subjects were instructed to aim for maximal height with contact times as fast as possible, keeping legs straight throughout the jumping sequence. All tests were performed twice and care was taken to ensure subjects maintained erect posture and landed toes first, in the same spot as takeoff. The following parameters were determined: peak force, time to peak force, peak power, maximum rate of force development and displacement. Leg stiffness was estimated by dividing the peak force by the vertical displacement measured during the 5-jump test (Cavagna et al., 1988).

7.3.2.4 Resistance-Training Interventions

The resistance training interventions were implemented during week 4 of the competitive season. While maintaining their normal endurance running training, each athlete performed two resistance-training sessions per week over a 7 to 10-wk period, with the exception of weeks 10, 12 and 13 prior to championship competitions where athletes performed only one session (Table 13, Session 1). Specific details of each resistance training session are presented in Table 13. Briefly, a familiarization session occurred during week 3 and involved a measure of each athletes 3 to 6 repetition max (RM) for the leg press exercise followed by a familiarization with each of the prescribed exercises. Each subjects 3 to 6 RM was converted to a 1 RM by the 1RM prediction equation of Lander (1985) (Lander, 1985). Both HRT and PRT programs were periodized throughout the competitive season and matched for volume load throughout the study based on the methods of Stone et al. (1999, 2007) (Stone, Stone, & Sands, 2007). Volume load for HRT and PRT was estimated for each training session using the number of sets, reps, load and body mass of subjects (Stone et al., 1999; Stone et al., 2007). Each resistance training session included 4 lower body lifts or 4 complex set lifts which included the identical lifts of the HRT group immediately followed by a plyometric exercise of a similar movement pattern (Table 13). Additionally all athletes performed the same upper body lifts during each session. Resistance training sessions occurred approximately 30 min after endurance training sessions and athletes were provided with details of the session (sets, repetitions, and weight) upon arrival to

the gym. Weights for each athlete were uncontrolled, but recommendations were given based on the previous sessions performance and subjects were encouraged to improve each week. All sessions were monitored and careful attention was given to each athlete to ensure good technique. Athletes were required to record details of all training sessions (resistance and endurance) undertaken during the course of the study. For each resistance training session, the weight (kg) and completed repetitions for each set was recorded, and for each endurance-training session, the training distance (km), and duration (min) were recorded.

Table 13: Nine-week resistance training program

Heavy exercise (Plyometric exercise) ^a		Week								
		4 – 5		6 – 8		9 – 10		11 – 13 ^c		
		HRT	PRT ^b	HRT	PRT	HRT	PRT	HRT	PRT	
Session 1	1	Back squat (Box Jump)	2× 6	1× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
	2a	SL calf raise (SL forward hop)	2× 10	1× 10/10	4× 10	4× 10/10	4× 12	3× 12/12	2× 10	1× 10/10
	2b	Dumb bell military press	2× 15	2× 15	4× 20	4× 20	4× 15	4× 15	2× 15	2× 15
	3a	Glute/hamstring raise (CMJ)	2× 10	1× 10/10	4× 6	3× 6/8	4× 8	3× 8/10	2× 6	1× 6/10
	3b	Lateral pull down	2× 15	2× 15	4× 20	4× 20	4× 15	4× 15	2× 15	2× 15
	4	Box step-up (Alternate leg bound)	2× 6	1× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
Session 2	1	Dead lift (Tuck jump)	4× 6	3× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
	2a	SL calf raise (SL box jump)	4× 6	3× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
	2b	Dumb bell incline bench press	4× 15	4× 15	4× 20	4× 20	4× 15	4× 15	2× 15	2× 15
	3a	Resisted monster walk (Side shuffle)	4× 8	3× 8/8	4× 10	4× 10/10	4× 12	3× 12/12	2× 10	1× 10/10
	3b	Pull-up	4× max	4× max	4× max	4× max	4× max	4× max	2× max	2× max
	4	Bulgarian split squat (Scissor jump)	4× 6	3× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10

SL = single leg. CMJ = countermovement jump. HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training.

^aResistance training exercises are listed as the heavy-resistance training exercise (performed by both HRT and PRT groups) followed by the plyometric exercise (performed only by PRT).

^bValues are number of sets × number of repetitions per set. Sets and repetitions are listed for HRT first (e.g. 4× 5) followed by sets and repetitions for PRT, listed as the number of sets × number of repetitions for each heavy/plyometric exercise (e.g. 3× 5/8 = 3 sets of 5 repetitions of the heavy exercise followed immediately by 8 repetitions of the plyometric exercise).

^cResistance training during weeks 11 through 13 was only performed by the top (fastest 7) athletes competing in championship events during weeks 12 and 13.

7.3.3 Performance During the Competitive Season

The competitive season occurred over a 10 to 13 week duration (Figure 13). Season length was dependent upon both the individual and team achievement at championship competitions (weeks 10, 12 and 13). Only the top (fastest) seven athletes from a team competed in the regional (week 12) and national (week 13) competitions. Athletes competed in various cross-country competitions throughout the competitive season ranging from 5- to 8-km for men and 5- to 6-km for women. NCAA cross-country competition data were downloaded from selected team websites for the entire cross-country season. Each performance time was rounded to the nearest 0.1 s. To focus on the training team (DXC) where the resistance training interventions were implemented, we selected data only from teams that directly competed against our intervention squad at least one time throughout the competitive season. Individuals that did not compete in at least 4 competitions during the season including their teams' inaugural and championship events were not included in the analysis. This selection process resulted in a total of 1741 individual performances in 37 competitions on 16 dates by 325 male athletes from 23 teams and 1652 individual performances in 37 competitions on 16 dates by 285 female athletes from 22 teams.

7.3.4 Analyses

Spreadsheets (Hopkins, 2007b) were used to analyse effects of training on laboratory-test measures. Analyses of changes within each group were made using the post-only crossover spreadsheet. Comparisons of the changes between groups were made with the pre-post parallel-groups spreadsheet. The pre-test value of the dependent variable was included as a covariate to improve precision of the estimate of the effects. The parallel-groups spreadsheet also allowed assessment of the magnitude of the differences between the two training groups arising from randomization at baseline.

Several analyses of the competition data were performed, all with mixed linear models similar to that of Vandenberg et al. (2012) (Vandenberg et al., 2012) using Proc Mixed in the Statistical Analysis System (Version 9.2, SAS Institute, Cary, NC). Mean performances of each of the three training groups (PRT, HRT, control) at each competition were estimated by inclusion of the identity of each competition as a fixed effect interacted with the group effect. Random effects in the model included the identity of the athlete (to account for differences in their ability), the interaction of the identity of the team with the identity of the competition (to account for the interdependence of athletes clustered within each team), and the residual error

(representing within-athlete variability in performance between competitions). Effects for female and male runners were estimated in separate analyses. From these analyses, it was apparent that the mean performance times of the control athletes were substantially slower than those of the training team (DXC). The solution for the random effect for athlete was therefore used to filter out slower control runners. Mean performances in the three groups across all competitions were similar when control female athletes with values of their random effect >3 (i.e., more than 3% slower than the average athlete) were excluded; for males, the exclusion criterion was a value >5 . The analyses with the filtered athletes provided the means for the competitions shown in Figure 14.

The effects of the treatment on competition time were then estimated via dummy variables having values of 1 for the intervention team (DXC) and 0 for the other (control) teams. Each competition in the intervention period was assigned a different dummy variable. The fixed effect for the interaction of training group and competition in the previous model was replaced with a fixed effect for competition only. The mean effects of each of the two types of resistance training at each competition in the intervention period were estimated with additional fixed effects consisting of the interaction of each dummy variable with the identity of the training group (PRT, HRT, control). The overall means for each treatment and for both treatments combined were obtained by averaging the effects at the three competitions during Weeks 8-12. (The effects at the National Championship in Week 13 for the seven top women were not included in the women's overall mean.) Random effects for the athlete and for the interaction of team and competition were the same as in the previous model. Individual responses to the training at the first competition during the intervention period (Week 6) and averaged over the subsequent competitions (Weeks 8-12 for men; Weeks 8-13 for women) were estimated by including random effects consisting of the interaction of appropriate dummy variables with the identity of the athlete. To allow for the possibility that the runners became more consistent in their performance later in the season, a novel approach was taken by interacting a term representing within-athlete variability between competitions (the interaction of athlete and competition identities) with a dummy variable declining linearly from 1 to 0 between the first and last competitions of the season. One value for this random effect was estimated for the training team and one for the control teams; similarly a different residual error was specified for the training and control teams, to allow for any difference in consistency of performance of these two groups of athletes.

Effects on dependent variables were estimated in percent units via log transformation. Uncertainty in the estimates of effects on performance (peak speed and competition time) was expressed as 90% confidence limits and as probabilities that the true value of the effect was beneficial, trivial or harmful in relation to threshold values for benefit and harm. These probabilities are not presented quantitatively but were used to make a qualitative probabilistic clinical inference about the effect (Hopkins et al., 2009). Briefly, the effect was deemed unclear when the chance of benefit was sufficiently high to warrant use of the treatment but the risk of harm was unacceptable. Such unclear effects were identified as those with an odds ratio of benefit to harm of <66 . All other effects were deemed clinically clear and assessed by estimating the probability that the true magnitude of the effect was at least as large as the observed magnitude. The threshold values for assessing the magnitude for small, moderate and large beneficial or harmful effects on performance were $\pm 0.5\%$, $\pm 1.5\%$, $\pm 2.7\%$ and $\pm 4.2\%$, which are approximately 0.3, 0.9, 1.6 and 2.5 of the within-subject standard deviation a top athlete would show between competitions (Hopkins et al., 2009). For top cross-country runners this standard deviation was 1.5-1.7% in a previous study (Hopkins & Hewson, 2001) and 1.3-1.5% by the end of the season in the current study (see Results). The probabilities were reported qualitatively using the following scale: 25-75%, possibly; 75-95%, likely; 95-99.5%, very likely; $>99.5\%$, most likely (Hopkins, 2007a). For the comparison of the effects in the two training groups, the probabilities of benefit and harm of plyometric resistance training were assessed relative to heavy resistance training, which was regarded as the reference or best-practice approach. Magnitudes of effects on measures other than performance were evaluated non-clinically (mechanistically) (Hopkins et al., 2009): if the confidence interval overlapped thresholds for substantial positive and negative values (± 0.20 standardized units, i.e., 0.20 of the between-subject SD of the dependent in the pre-test), the effect was deemed unclear; all other effects were reported as the magnitude of the observed value and were evaluated probabilistically as described above, except that threshold values for assessing magnitudes of standardized effects were 0.20, 0.60 and 1.2 for small, moderate and large respectively (Hopkins et al., 2009).

7.4 Results

The proportion of training session's athletes attended during the competition season was $97 \pm 3\%$ (mean \pm SD). Before the competition season PRT and HRT groups were similar for men and for women in 5-km time-trial performance, training volume, and body fat, but there were small to moderate differences between groups in body mass, age, and training history (Table 12). During the competition season men performed on average $15.7 \text{ km}\cdot\text{wk}^{-1}$ of training above 80 percent of VO_2max and the

women performed $14.6 \text{ km}\cdot\text{wk}^{-1}$, which was equivalent to $17.2 \pm 2.5 \%$ of men's and $20.7 \pm 4.0 \%$ of women's weekly training volume (Table 12). There was no substantial change in body mass from pre to post testing in men or women, and differences between groups were unclear. Small to moderate reductions in percent body fat were found within both male PRT (mean change score (%) \pm SD; \pm CL, -9.7 ± 23.0 ; ± 10.8) and HRT (-18.5 ± 20.5 ; ± 11.4) and both female PRT (-6.9 ± 9.4 ; ± 6.6) and HRT (-11.8 ± 12.6 ; ± 7.9) groups, but PRT had a possibly small negative effect relative to HRT. Baseline values of other outcome measures, statistics for effects, and inferences about the interventions within and between groups for men and women are presented in Tables 14 and 15 respectively.

Table 14: Male outcome measures at baseline and statistics for effects and inferences about the interventions within and between groups.

	Group 1 (PRT)		Group 2 (HRT)		Group Comparison (1 – 2)	
	Baseline values (mean ± SD)	Change score (%) (mean ± SD; ±CL)	Baseline values (mean ± SD)	Change score (%) (mean ± SD; ±CL)	Difference between groups (% mean ±CL)	Qualitative inference ^a
Performance Measures						
Peak speed	20.1 ± 1.2 km·h ⁻¹	1.0 ± 3.7; ±1.8	19.6 ± 1.1 km·h ⁻¹	4.6 ± 4.5; ±2.6	-3.4; ±3.0	small harm**
Aerobic Measures						
VO ₂ max	63.8 ± 4.6 ml·kg ⁻¹ ·min ⁻¹	0.1 ± 5.2; ±2.6	63.7 ± 4.7 ml·kg ⁻¹ ·min ⁻¹	1.2 ± 7.1; ±4.1	-1.1; ±4.6	unclear
vVO ₂ max	17.5 ± 0.8 km·h ⁻¹	0.3 ± 3.9; ±1.9	17.5 ± 1.1 km·h ⁻¹	1.6 ± 4.9; ±2.8	-1.3; ±3.3	unclear
RE at 14km·h ⁻¹	50.8 ± 3.2 ml·kg ⁻¹ ·min ⁻¹	-0.2 ± 3.3; ±1.6	51.3 ± 3.3 ml·kg ⁻¹ ·min ⁻¹	-1.7 ± 4.1; ±2.3	1.5; ±2.7	small -ive*
RE at 14km·h ⁻¹	218 ± 13 ml·kg ⁻¹ ·km ⁻¹	-0.2 ± 3.3; ±1.6	221 ± 14 ml·kg ⁻¹ ·km ⁻¹	-2.1 ± 4.5; ±2.6	2.0; ±3.0	small -ive*
%VO ₂ at 14km·h ⁻¹	79.7 ± 4.2 %VO ₂ max	-0.2 ± 3.9; ±1.9	80.7 ± 4.0 %VO ₂ max	-2.8 ± 5.1; ±2.9	2.7; ±3.4	small -ive**
Biomechanical Measures						
Contact time	0.24 ± 0.02 s	-2.6 ± 5.6; ±2.7	0.23 ± 0.01 s	0.9 ± 2.4; ±1.4	-3.5; ±3.0	small +ive**
Flight time	0.12 ± 0.02 s	9.3 ± 17.1; ±8.1	0.12 ± 0.02 s	-1.8 ± 5.4; ±3.1	11.3; ±8.6	moderate +ive*
Neuromuscular Measures						
1RM	68.7 ± 13.6 kg	24.3 ± 5.6; ±2.7	70.7 ± 13.3 kg	31.1 ± 3.5; ±2.0	-5.2; ±3.3	small -ive**
Stiffness	9.6 ± 2.0 kN·m ⁻¹	-3.0 ± 22.5; ±10.5	9.3 ± 2.0 kN·m ⁻¹	15.0 ± 20.7; ±11.5	-15.7; ±15.2	moderate -ive*
5-Jump Test						
Peak force	64.6 ± 12.3 N·kg ⁻¹	3.5 ± 11.4; ±5.5	65.2 ± 5.8 N·kg ⁻¹	10.0 ± 9.3; ±5.3	-5.9; ±7.4	small -ive**
Peak power	67.2 ± 19.2 W·kg ⁻¹	0.4 ± 21.1; ±9.9	68.5 ± 16.4 W·kg ⁻¹	0.5 ± 5.8; ±3.3	-0.1; ±10.4	unclear

HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training. SD = standard deviation. CL = confidence limits. 1RM = one repetition max. VO₂max = maximal aerobic capacity. vVO₂max = velocity at VO₂max. RE = running economy. %VO₂max = percent of VO₂max. +ive = positive or beneficial effect on Group 1 as compared to Group 2. -ive = negative or harmful effect on Group 1 as compared to Group 2.

^aThe inference for performance is clinical; those for other measures are non-clinical.

*25-75%, possible; **75-95%, likely; ***95-99.5%, very likely; ****>99.5%, most (or extremely) likely

≥0.2 small; ≥0.6 moderate; ≥1.2 large; ≥2.0 very large; ≥4.0 extremely large

Table 15: Female outcome measures at baseline and statistics for effects and inferences about the interventions within and between groups.

	Group 1 (PRT)		Group 2 (HRT)		Group Comparison (1 – 2)	
	Baseline values (mean ± SD)	Change score (%) (mean ± SD; ±CL)	Baseline values (mean ± SD)	Change score (%) (mean ± SD; ±CL)	Difference between groups (% mean ±CL)	Qualitative inference ^a
Performance Measures						
Peak speed	17.6 ± 0.7 km·h ⁻¹	2.2 ± 3.7; ±2.3	17.2 ± 1.0 km·h ⁻¹	4.4 ± 3.9; ±2.2	-2.2; ±3.0	small harm*
Aerobic Measures						
VO ₂ max	51.3 ± 2.8 ml·kg ⁻¹ ·min ⁻¹	4.7 ± 5.2; ±3.2	52.3 ± 3.3 ml·kg ⁻¹ ·min ⁻¹	3.4 ± 6.3; ±3.6	1.3; ±4.6	unclear
vVO ₂ max	15.3 ± 0.9 km·h ⁻¹	2.3 ± 4.5; ±2.8	15.2 ± 0.9 km·h ⁻¹	1.6 ± 5.2; ±3.0	0.7; ±3.9	unclear
RE at 14km·h ⁻¹	43.9 ± 2.3 ml·kg ⁻¹ ·min ⁻¹	-1.0 ± 2.2; ±1.3	44.9 ± 1.9 ml·kg ⁻¹ ·min ⁻¹	-3.4 ± 4.1; ±2.4	2.5; ±2.6	small -ive**
RE at 14km·h ⁻¹	203 ± 10 ml·kg ⁻¹ ·km ⁻¹	-1.5 ± 3.5; ±2.1	207 ± 9 ml·kg ⁻¹ ·km ⁻¹	-3.4 ± 4.1; ±2.4	1.9; ±3.0	small -ive*
%VO ₂ at 14km·h ⁻¹	84.8 ± 5.5 %VO ₂ max	-3.9 ± 4.0; ±2.5	84.6 ± 5.7 %VO ₂ max	-3.2 ± 4.0; ±2.3	-0.7; ±3.2	unclear
Biomechanical Measures						
Contact time	0.24 ± 0.02 s	-1.1 ± 3.8; ±2.4	0.24 ± 0.01 s	4.2 ± 2.6; ±1.6	-5.0; ±2.7	moderate +ive**
Flight time	0.09 ± 0.01 s	4.2 ± 15.2; ±9.2	0.10 ± 0.02 s	-10.2 ± 12.5; ±7.6	16.0; ±11.3	moderate +ive**
Neuromuscular Measures						
1RM	41.2 ± 8.0 kg	29.6 ± 8.7; ±5.3	35.9 ± 2.3 kg	44.5 ± 10.3; ± 5.8	-10.3; ±7.5	moderate -ive*
Stiffness	13.6 ± 1.5 kN·m ⁻¹	4.5 ± 10.4; ±6.3	13.5 ± 1.5 kN·m ⁻¹	11.5 ± 12.1; ±6.9	-6.3; ±8.9	moderate -ive*
5-Jump Test						
Peak force	70.7 ± 14.3 N·kg ⁻¹	1.1 ± 14.3; ±8.6	64.9 ± 14.8 N·kg ⁻¹	7.5 ± 14.8; ±8.3	-5.9; ±11.5	unclear
Peak power	53.4 ± 12.2 W·kg ⁻¹	-6.3 ± 20.8; ±12.4	48.2 ± 11.2 W·kg ⁻¹	5.3 ± 13.1; ±7.4	-10.9; ±14.0	small -ive**

HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training. SD = standard deviation. CL = confidence limits. 1RM = one repetition max. VO₂max = maximal aerobic capacity. vVO₂max = velocity at VO₂max. RE = running economy. %VO₂max = percent of VO₂max. +ive = positive or beneficial effect on Group 1 as compared to Group 2. -ive = negative or harmful effect on Group 1 as compared to Group 2.

^aThe inference for performance is clinical; those for other measures are non-clinical.

*25-75%, possible; **75-95%, likely; ***95-99.5%, very likely; ****>99.5%, most (or extremely) likely

≥0.2 small; ≥0.6 moderate; ≥1.2 large; ≥2.0 very large; ≥4.0 extremely large

7.4.1 Performance and Aerobic Measures

There were only small differences at baseline between groups for peak speed and running economy ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) in men and women, for vVO_2max and $\%\text{VO}_2\text{max}$ in men, and for VO_2max and running economy ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) in women. Mean improvements in peak speed of small to very large magnitude were observed in both groups for men and women, but PRT was clearly harmful relative to HRT (Table 14 and Table 15). Following the intervention period male HRT showed small or moderate improvements in aerobic measures, whereas the effects from PRT on aerobic measures were trivial (Table 14). Both female groups showed small to moderate improvements in all aerobic measures (Table 15). Male and female HRT showed greater improvements in running economy compared with PRT. Differences between groups on all other aerobic measures were unclear.

7.4.2 Biomechanical Measures

In both training groups and both sexes, changes in contact time were opposite to those of flight time. The direction of the changes were opposite in the two training groups, and overall the changes with PRT were clearly positive and small-moderate in magnitude relative to those with HRT (Table 14 and Table 15).

7.4.3 Neuromuscular Measures

One-repetition max (1RM) improved in all groups, with male athletes improving by 20-40% (Table 14) and female athletes improving by 30-50% (Table 15). Improvements were greater with HRT. Changes in neuromuscular related measures from the 5-jump test were small to moderate improvements with HRT and trivial or negative with PRT (Table 14 and Table 15). Overall, PRT was associated with either unclear or negative effects on all neuromuscular measures in men and women. There was a moderate improvement in leg stiffness after HRT in men and women and unclear decrease (male) or possibly small improvement (female) after PRT (Table 14 and Table 15 respectively).

7.4.4 Competition Measures

The residual error in competition times calculated at the beginning of the season was $\sim 2.0\%$ for the training and control groups and at the end of the season was 1.3-1.4% in the training groups and 1.5% in the control group. Figure 2 shows the least-squares mean performance times for men and women in the competitions that the training groups entered. The mean effects of the training interventions on performance at each competition were generally consistent from Week 8 through the

end of the season for male and female athletes. Overall, PRT resulted in possible harm to competition times (slower run times) by 0.8% (90% confidence limits $\pm 1.5\%$) compared to control male athletes. Heavy-resistance training (HRT) was also possibly harmful to competition performance (0.1%; $\pm 1.3\%$). The men's overall mean performance was worse (slower) than that of the control teams by 0.5% ($\pm 1.2\%$) after implementation of the two resistance-training interventions. There was an unclear difference between PRT and HRT ($-0.7 \pm 1.5\%$). There was a likely beneficial effect of PRT training for females, resulting in -1.1% ($\pm 1.3\%$) faster run times (compared to control female athletes). Heavy-resistance training was also likely beneficial to competition performance, -1.4% ($\pm 1.4\%$). The women's overall mean performance was better (faster) than that of control teams by -1.2% ($\pm 1.3\%$). When compared to HRT, PRT was possibly harmful (0.3%; $\pm 1.0\%$). Individual responses expressed as a standard deviation for both treatments combined was 0.3% (90% confidence interval -1.2% to 1.3%) for men and -0.6% (-1.0% to 0.5%) for women.

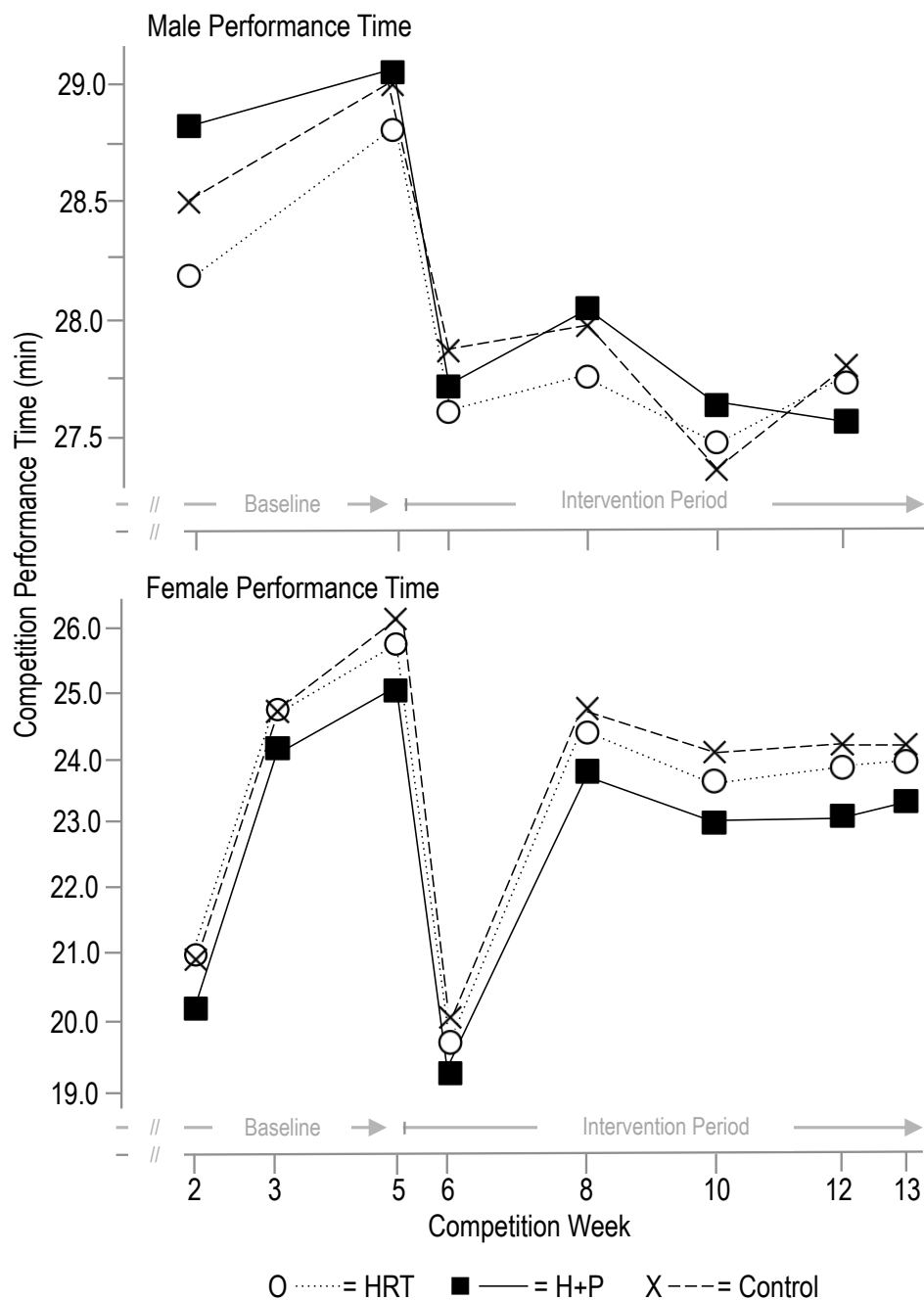


Figure 14: Least-squares mean of male and female performance times.

7.5 Discussion

Previous studies (Hickson et al., 1988; Paavolainen, Hakkinen, et al., 1999; Spurr et al., 2003) have reported that various forms of resistance training may lead to improved endurance performance in trained subjects. However, the optimal prescription of resistance training to improve endurance running performance has yet to be firmly established. Accordingly, we investigated whether the combination of plyometric training and heavy-resistance training (PRT) may facilitate additional

improvements in neuromuscular efficiency, strength, and running mechanics, compared to heavy resistance-training (HRT) alone during the competition phase of a men's and women's collegiate cross-country season. Interestingly, our data revealed distinct differences between the prescribed training regimes in terms of performance gains and physiological adaptations, and an apparent gender-specific response to resistance training.

To determine the effects of HRT and PRT on performance from competition data, the coefficient of variation (CV) representing typical variation in performance time for the faster male and female runners across the competition season was determined. The CV sets the benchmark for the smallest worthwhile change in an athlete's performance and for the typical (standard) error of measurement of tests used to assess the smallest important or worthwhile change (Hopkins et al., 2009). Our CV of ~2.0% at the start of the competitions and ~1.5% at the end are in line with the 1.5-1.7% reported by Hopkins and Hewson (Hopkins & Hewson, 2001) and were the basis of using a $\pm 0.5\%$ threshold value for beneficial and harmful effects on performance (approximately 0.3 of the within-subject standard deviation top athletes show between competitions (Hopkins & Hewson, 2001; Hopkins et al., 2009). Accordingly, there were substantial beneficial mean effects on competition performance for the female training groups compared to controls ($-1.2 \pm 1.3\%$), whereas resistance training for males proved to be possibly harmful ($0.5 \pm 1.2\%$). This observation could be an indication that endurance-trained female athletes may have a greater requirement in terms of resistance training maintenance (Peterson, Pistilli, Haff, Hoffman, & Gordon, 2011), whereas this type of training for men might be beneficial in general only during the pre-season or build-up phase of training when there is less emphasis on competition and gains can be made in physiological measures without the risk of harm to competition performance. Further, the resistance training programs may not have been optimal to elicit a maximal physiological and/or neuromuscular response following training. There is some evidence to suggest that concurrent resistance and endurance training inhibits strength development (Leveritt, Abernethy, Barry, & Logan, 2003; Leveritt, Abernethy, Barry, & Logan, 1999). Other research suggests the order of training (endurance then strength or strength then endurance) could affect outcomes (Chtara et al., 2005; Chtara et al., 2008; Leveritt et al., 2003). The changes in this study suggest otherwise given the large improvements in 1-RM, however this was to be expected in a group novice lifters. While the enhancements in various neuromuscular parameters were to be expected given the population of this study, perhaps these changes were not great enough to improve cross-country running performance to a greater degree. Other research suggests the order of exercises and recovery between exercises can

substantially affect neuromuscular changes (Chtara et al., 2005; Chtara et al., 2008; Leveritt et al., 2003). Perhaps if changes in the choice, order and recovery between exercises could elicit greater improvements in performance, however, further research is required to elucidate these possibilities. Lastly, the differences in effects between men in women could also be due in part to differences in training intensity and competition distance. The proportion of training that occurred at $\geq 80\%$ VO_2max for females was moderately higher than that for males (Table 12), which might have translated into performance enhancement over the women's shorter race distance (5-6 km vs 8-10 km for the men). Although we observed an overall benefit in competition performance from either form of resistance training in women and harm in men, HRT was substantially better for females (0.3%; $\pm 1.0\%$) while PRT was worse (-0.7 $\pm 1.5\%$).

In addition to actual competition data, we also observed a substantial increase in laboratory-derived peak running speed following HRT (4.6% and 4.4% in men and women respectively) compared to PRT (1.0% and 2.2% in men and women respectively). Peak running speed has been shown to be a good indicator of endurance performance in middle- and long-distance running events (Billat & Koralsztejn, 1996; Noakes, 1988; Noakes, Myburgh, & Schall, 1990; Saunders, Cox, Hopkins, & Pyne, 2010; Stratton et al., 2009) and Noakes (Noakes, 1988; Noakes et al., 1990) has suggested that peak running speed could be used as a measure of the 'muscle power' factor in endurance runners. Muscle power is defined as an ability of the neuromuscular system to produce power during maximal exercise when glycolytic and/or oxidative energy production are high and muscle contractility may be limited (Noakes, 1988). Indeed, in addition to the aerobic processes related to distance running performance, the neuromuscular and anaerobic characteristics related to peak running speed are also strongly involved in distance running performance.

In the present study, changes in physiological measures related to distance running performance were consistent with performance data, indicating greater improvements following HRT than matched volume-load PRT (Table 14 and Table 15). Specifically, the addition of HRT improved running economy by 1.7% and 3.4% in males and females respectively, while PRT only improved running economy by 0.2% and 1.0% [Table 14 (men), Table 15 (women)]. Although both HRT and PRT results are in accordance with growing literature demonstrating that heavy resistance-training or plyometric training improved the running economy of well-trained athletes ((Guglielmo et al., 2009; Johnston et al., 1997; Millet et al., 2002; Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Storen et al., 2008; Turner et al., 2003), the magnitude of enhancements were lower in our study

compared to previous studies reporting effects following heavy-resistance (Guglielmo et al., 2009; Johnston et al., 1997; Millet et al., 2002; Storen et al., 2008) or plyometric training (Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Turner et al., 2003). This could be due to different phases of season that the studies were performed. Regardless, in both HRT and PRT, improvements in running economy occurred in the absence of any substantial change in VO_2 max suggesting that improved running economy was a result of neuromuscular characteristics rather than improved cardiorespiratory fitness. This is a reasonable assertion since both HRT and PRT groups performed the same endurance training outside of their respective resistance training programs. In further support, running economy improved in accord with many of the neuromuscular measures (Table 14 and Table 15) which also aligns well with previous studies (Dalleau et al., 1998; Millet et al., 2002; Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Storen et al., 2008) reporting the importance of the neuromuscular characteristics in determining running economy and running performance following combined resistance and endurance training in runners.

With regards to changes in strength and neuromuscular measures that could be responsible for the greater improvements in running economy and peak running speed following HRT, it has been purported (3, 26) that the nervous system plays an important role in regulating muscle stiffness and utilization of muscle elasticity during stretch-shortening cycle exercises, such as running, in which high contraction velocities are used. In the present study, small to moderate increases in leg stiffness occurred in the male and female HRT groups and PRT training was associated with moderate negative effects on leg stiffness compared to HRT (Table 14 and Table 15). Interestingly, the group with the smallest improvement in 1RM (male PRT) was the only group not to elicit a concomitant increase in stiffness. One of the most important roles of the muscle during running is to modulate leg stiffness and storage-recoil of energy. The conversion of energy to motion involves recoil of some elastic energy in muscle and tendon, thus a “stiffer” muscle or tendon would be better at transferring energy economically or without the need for additional oxygen consumption (Cavagna & Kaneko, 1977; Dalleau et al., 1998; Spurrs et al., 2003). Indeed, previous evidence has shown a negative correlation between leg stiffness and cost of running (Albracht & Arampatzis, 2006; Arampatzis et al., 2006). Kerdok et al. (Kerdok, Biewener, McMahon, Weyand, & Herr, 2002) have shown changes in both muscle-tendon stiffness and running economy when manipulating the running surface, indicating that runners adjust the level of leg stiffness towards the most optimal degree, to maintain consistent running mechanics on different surfaces. This could be important,

particularly in cross-country runners like those in the present study where competitions often take place on a variety of undulating surfaces in a single competition. Conversely, the training-induced alterations in biomechanical measures support PRT training and therefore are not likely related to the changes in running economy, peak speed or competition performance. Other studies have indicated that these biomechanical adaptations also occurred in response to plyometric training (Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006). Collectively, these findings suggest that HRT had a positive influence on cross-country running performance because of the improved running economy, peak speed and neuromuscular characteristics.

Finally, it was not surprising to observe the magnitude of improvement in maximal strength (20-40% in the leg press for most athletes) in our sample of distance-runners with limited resistance-training experience. The enhancements in 1RM strength from HRT were 30 and 50% percent greater than PRT in men and women respectively, indicating a positive effect to HRT on strength parameters. The increased muscular strength due to resistance- and/or plyometric-training might primarily come from neural adaptations without observable muscle hypertrophy (Hakkinen, 1994; Sale, 1988). The finding that no substantial change in body weight and small to moderate reductions in percent fat in both PRT and HRT groups, suggesting that little, if no hypertrophy occurred due to the resistance training interventions supports this suggestion. Increases in body mass are an undesirable side effect to resistance training that could be counter-productive to distance running performance.

In conclusion, both HRT and PRT had a likely beneficial effect on competition times in females while both treatments had possibly harmful effects in males. However, when comparing the two treatments, the addition of plyometric training to heavy resistance training was harmful to cross-country competition performance and most laboratory-based measures when compared to a matched volume-load heavy resistance-training program. The greater improvements in competition performance and an enhancement in running economy and peak speed following HRT, compared to PRT, was probably a result of improvements in lower limb strength, leg stiffness and utilization of stored elastic energy. Overall, our data indicate that females should include heavy-resistance training in their programs, but males may want to implement such training in-season with caution until more research establishes characteristics of positive or negative responders.

7.6 Acknowledgements

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CHAPTER 8: OVERALL DISCUSSION & CONCLUSION

A comprehensive review of the literature at the outset of this work, highlighted a number of limitations in regards to the current understanding of what running economy represents as well as which specific strategies can improve running economy in trained distance runners. Of the numerous metabolic, cardiopulmonary, biomechanical and neuromuscular factors affecting running economy, it appears that a few common mechanisms were subject to alteration or improvement through purposeful training. Furthermore, while a variety of strategies to improve running economy had been investigated (Figure 6), the efficacy of resistance training appeared to be most promising and practical method. Although a number of studies had examined either traditional resistance training (Berryman et al., 2010; Guglielmo et al., 2009; Johnston et al., 1997; Sedano et al., 2013; Storen et al., 2008) or plyometric training (Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Turner et al., 2003) independently as a means of improving running economy, the evidence supporting either form was conflicting. Additionally, while traditional resistance training and plyometric training are common ancillary training practices for distance runners who choose to adopt them, other forms of resistance exercise such as running uphill or with a weighted vest are also performed by distance runners during training, yet there was limited information in regards to the physiological responses to warrant such training practices. Principally, there was an apparent dearth of studies that have examined the effects of movement-specific modes of resistance exercise on running economy and performance. Accordingly, this thesis attempted to address these limitations, according to the main paradigm of interest: what is the relative efficacy of different forms of movement-specific resistance exercise to improve running economy and performance in training distance runners? A summary of the chapters included as part of this thesis is presented in Table 16. Subsequent discussion in this section articulates the main findings of this thesis in regards to the individual research questions underpinning the aim of this thesis.

Table 16: Summary of the chapters included as part of the thesis.

Chapter	Title	Subjects	Study Design	Training	Performance and Physiological Tests	Findings
Chapter 2	Running economy: measurement, norms and determining factors	n/a	Literature review	n/a	n/a	n/a
Chapter 3	Strategies to improve running economy	n/a	Literature review	n/a	n/a	n/a
Chapter 4	Lower body determinants of running economy in male and female distance runners	63 moderately-trained runners (39 males, 24 females)	Cross-sectional descriptive design	n/a	Running economy; incremental step test; CMJ; SJ; 5J; biomechanical analysis	Lower-body stiffness and moment arm length of the Achilles tendon are substantially related to running economy. Lower-body stiffness was also related to Achilles moment arm length.
Chapter 5	Warm-up with a weighted vest improves running performance via leg stiffness and running economy	11 well-trained male runners	Randomized, Cross-over design	6 × 10-s strides with or without weighted vest	Running economy; incremental step test; CMJ; SJ; 5J	Strides with a weighted vest during a traditional warm-up enhances subsequent running performance (peak speed) and running economy. The mechanisms analysis suggests changes in leg stiffness could explain all the changes in performance and running economy.
Chapter 6	Effects of different uphill interval-training programs on running economy and performance	20 moderately-trained male runners	Pre-post parallel-groups dose-response design	2 d/wk for 6-wk various uphill interval training programs	5-km time trial on tartan track, running economy; incremental step test; CMJ; SJ; 5J	Running performance improved across the range of training intensities without a strong curvilinear relationship between uphill-training characteristics and a subsequent change in 5-km time-trial performance or peak running speed. Training at the highest intensities was associated with the greatest improvements in running economy and neuromuscular characteristics, as well as increased stride rate.
Chapter 7	Effects of resistance training on running economy and cross-country performance	50 moderately-trained runners (28 males, 22 females)	Pre-post parallel-groups design	10-13 wk cross-country running training + 2 d/wk HRT or PRT	5 to 8-km cross country competitions, running economy; incremental step test; 5J; biomechanical analysis; 1-RM	HRT and PRT are likely beneficial on competition times in women, whereas both treatments possibly harmful in men. PRT was harmful to cross-country competition performance and most laboratory-based measures when compared with a matched volume-load HRT

program. The greater improvements in competition performance and an enhancement in running economy and peak speed after HRT, compared with PRT was probably a result of improvements in lower limb strength, leg stiffness, and utilization of stored elastic energy.

HRT = Heavy resistance training; **PRT** = Plyometric resistance training; **CMJ** = Countermovement Jump; **SJ** = Squat Jump; **5J** = 5 Jump plyometric test; **1-RM** = 1 repetition max

8.1 Research Questions

8.1.1 What are the lower-body determinants of running economy among male and female trained distance runners?

Despite the performance benefits of being an economical runner, researchers have yet to resolve why some runners demonstrate markedly better economy when compared to counterparts exhibiting similar fitness, training history and performance backgrounds (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Daniels, Krahenbuhl, et al., 1977; Williams & Cavanagh, 1987). While Chapter 2 comprehensively reviewed the metabolic, cardiorespiratory, biomechanical and neuromuscular factors that may affect the measurement of running economy, and Chapter 3 discussed the current state of knowledge in regards to improving running economy, the findings of Chapter 4 begin to elucidate some of the lower-body determinants of running economy (Barnes, McGuigan, & Kilding, in press), which may be useful to explain differences between individuals or groups of runners or provide mechanisms to explain changes following training. A range of trainable and non-modifiable factors were identified as determinants of running economy. Of interest, leg stiffness ($r = -0.80$) and moment arm length ($r = 0.90$) were large-extremely largely correlated with running economy. These results were similar to other studies (Arampatzis et al., 2006; Dumke et al., 2010), which demonstrated that lower body stiffness is substantially related to running economy of well-trained runners. The relationship between moment arm length and running economy was expected based on a simple musculoskeletal model of tendon energy storage (Scholz et al., 2008) but the magnitude of this relationship ($r = 0.90$) was considerably larger than previously reported by Raichlen et al. (2011) ($r = 0.64$) and Scholz et al. (2008) ($r = 0.77$) using small sample sizes of 8 and 15, respectively (Raichlen et al., 2011; Scholz et al., 2008). This study also showed that lower body stiffness was related to the moment arm of the Achilles tendon ($r = -0.82$) (Figure 9). This is a unique finding not previously reported in the literature and suggests the Achilles moment arm length may affect stiffness properties following training. Although Achilles moment arm length is a non-modifiable factor affecting running economy, for practitioners this is an easy determinant to measure and may help scientists and coaches understand why some athletes have good, average or poor economy and may also be a determinant of setting the upper and lower limits of an individual's ability to improve their running economy following training.

8.1.2 What is the efficacy of augmenting running economy and performance acutely?

Prior warm-up activities are a widely accepted practice preceding nearly every athletic event to prepare the body for optimal competition performance (Bishop, 2003). An active warm-up is arguably the most widely used warm-up technique for distance runners because it is likely to induce specific metabolic and cardiovascular changes conducive to distance-running performance (Bishop, 2003). Recent research has focused on various warm-up exercises that can alter oxygen uptake (VO_2) kinetic responses to subsequent high-intensity exercise and enhance performance (Bishop et al., 2001; Hajoglou et al., 2005; Ingham et al., 2013). However, neuromuscular characteristics have also been recognized as an important determinant of endurance performance (Paavolainen, Hakkinen, et al., 1999). Indeed, different training regimens over the course of several weeks to months have demonstrated concomitant improvements in neuromuscular measures, running economy and distance running performance (Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003). In Chapter 5, the acute effects of a warm-up while wearing a weighted vest on neuromuscular measures, running economy and distance running performance were examined. The weighted vest condition resulted in a very-large enhancement of peak running speed (2.9%; 90% confidence limits $\pm 0.8\%$), a moderate increase in leg stiffness (20.4%; $\pm 4.2\%$) and a large improvement in running economy (6.0%; $\pm 1.6\%$); there were also small-moderate clear reductions in cardiorespiratory measures. According to Hopkins (2001) the 2.9% improvement in performance should result in a similar change in running competition time (Hopkins et al., 2001). The effect was substantially greater than those in comparable studies. For example, Ingham et al. (2013) reported a 1.2 s ($\sim 1\%$) improvement in 800-m running performance following a high-intensity warm-up compared to a traditional warm-up similar to that in this study (Ingham et al., 2013). Interestingly, performance was enhanced despite a small negative effect on perceived race readiness, which suggested the underlying mechanism of the enhancement was more than enough to overcome some sense of fatigue induced by the weighted-vest regimen. The mechanisms analysis supported this premise, in that using a linear regression model for the change scores in performance and change scores in respective mechanism variables, we determined that of the 2.9% improvement in performance, 3.4% ($\pm 90\%$; ± 1.1) was associated with changes in stiffness, while the change not associated with improvements in leg stiffness was -0.5% ($\pm 1.2\%$), indicating the change in performance independent of changes in stiffness following weighted-vest condition would have actually resulted in a 0.5% impairment in performance.

Leg stiffness was moderately higher after weighted-vest strides compared with those of control strides (ES = 0.76). Acute changes in leg stiffness have also been reported in runners as a result of running on surfaces that differ in hardness (Ferris et al., 1999) or chronically, following several weeks of strength and plyometric training (Burgess et al., 2007; Spurrs et al., 2003) or high-intensity uphill interval-training (Barnes, Hopkins, et al., 2013b). The performance of skeletal muscle is affected by its contractile history; thus the explanation for the changes we observed in stiffness following warm-up with the weighted vest is likely related to the phenomenon of post-activation potentiation (Sale, 2002). Muscle and tendon are two springs in series; an increase in stiffness therefore results in more potential energy stored in muscle and tendon, less muscle activation for running at a given speed, and a reduction in energy expenditure (Dalleau et al., 1998; Spurrs et al., 2003). Indeed, the weighted-vest condition elicited a 6.0% or $\sim 3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ reduction in VO_2 during submaximal running. This is a unique finding in that no researchers have reported improvements in running economy following acute priming exercise, though our difference in running economy are similar (Millet et al., 2002; Paavolainen, Hakkinen, et al., 1999) or better than (Barnes, Hopkins, et al., in press) those demonstrated in previous studies following several weeks of resistance training in runners. Despite the effect of running economy on performance being unclear (0.8%; $\pm 2.1\%$), it was possible that economy is still a mediator linking the changes in stiffness to the changes in performance. After all, the improvement in running economy of 6.0%, other things being equal, would result in a $\sim 6\%$ enhancement in performance according to the model of di Prampero et al. (1993) (di Prampero et al., 1993).

8.1.3 What is the most effective uphill interval-training protocol to enhance running economy and performance?

While coaches often utilize various forms of movement-specific resistance training in periodized training programs for distance runners, only anecdotal reports (Kurz et al., 2000; Midgley et al., 2007; Saunders, Pyne, et al., 2004a) and two research investigations (Ferley et al., 2012; Houston & Thomson, 1977) existed concerning the physiological responses and potential improvements in performance to such training. In view of this uncertainty about the physiological effects of uphill training on distance running performance, Chapter 6 examined a variety of uphill interval-training approaches on running economy and performance in well-trained distance runners. To address this problem, we used a dose-response design previously reported by Stepto et al. (1999) in which each runner received only a single form of uphill interval-training, and the optimum training "dose" was identified by

modeling the effect of training as a polynomial function of the rank-ordered training intensity (Stepto et al., 1999).

We observed that training at the highest intensities was associated with the greatest improvements in running economy and neuromuscular characteristics as well as increased stride rate. Ours was the first study to demonstrate that a regimen of high-intensity uphill interval training improves running economy. The magnitude of the improvement (2.4%; $\pm 1.5\%$) is consistent with previous studies reporting positive effects of traditional resistance training or plyometric training on running economy in runners with a wide range of ability (Johnston et al., 1997; Millet et al., 2002; Paavolainen, Hakkinen, et al., 1999; Paavolainen, Nummela, & Rusko, 1999; Saunders et al., 2006; Spurrs et al., 2003; Storen et al., 2008; Turner et al., 2003) as well as anecdotal reports of the benefits of uphill sprinting (Kurz et al., 2000; Midgley et al., 2007; Saunders, Pyne, et al., 2004a). The fact that the greatest improvements in neuromuscular measures also occurred with the highest intensity of training supports the premise that the enhancement of running economy was due to a range of mechanisms relating to recruitment and coordination of muscle fibers, efficiency of muscle power development, as well as better use of the muscle-tendon units stored elastic energy (Cavagna et al., 1988). Training-induced alterations in stride rates were also greatest at the highest training intensity, however, it cannot be discounted that the changes in biomechanical measures may themselves be explained at least partly by changes in neuromuscular characteristics. Paavolainen et al. (1999) observed similar changes in stride characteristics in response to nine weeks of explosive-strength training in well-trained endurance runners along with concurrent $\sim 8\%$ improvement in running economy (Paavolainen, Hakkinen, et al., 1999).

Unfortunately no specific uphill-training approach was associated with greater gains in 5-km time trial performance. Running performance improved across the range of training intensities without a strong curvilinear relationship between uphill training characteristics and a subsequent change in 5-km time-trial performance or peak running speed. The 2% improvement in running performance was similar to other studies demonstrating concurrent improvements in running economy and performance while employing various modes of resistance training (Paavolainen, Hakkinen, et al., 1999; Spurrs et al., 2003). Ferley et al. (2012) also demonstrated a $\sim 2\%$ improvement in estimated time-trial performance (Hopkins et al., 2001) following 6 weeks of uphill-interval training similar to that of Group 2 training in our study (Ferley et al., 2012).

Our model predicted optimal enhancements in other aerobic measures (besides running economy) after work bouts associated with an intensity between Groups 3 and

4 training. The enhancements observed was unsurprising since the intensity of these work bouts occurred at or near VO_2max , which is in accord with the principle of specificity. It is highly likely these changes were a result of the additional uphill interval training because all subjects were undertaking similar running training outside of the present study ($95 \pm 25 \text{ km}\cdot\text{wk}^{-1}$). In contrast, the two studies utilizing uphill interval-training reported no change (Houston & Thomson, 1977) or a decrement in VO_2max (Ferley et al., 2012).

8.1.4 Does the addition of plyometric training to traditional heavy-resistance training enhance running economy and performance more than heavy resistance-training alone?

Heavy-resistance training and plyometric training offer distinct physiological, biomechanical and neuromuscular adaptations that could enhance running economy and consequently distance-running performance. Recent research has shown running economy to improve in runners using traditional strength training or explosive, plyometric training (Johnston et al., 1997; Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006), however, the optimal prescription of resistance training to improve endurance running performance had yet to be firmly established. In light of this limitation, Chapter 7 examined the efficacy of combining both heavy-resistance training and plyometric training to facilitate additional improvements in running economy via an accumulation of adaptations previously observed when either type of training is performed alone. Given there was a strong association between running economy and distance running performance (Barnes, Hopkins, McGuigan, & Kilding, 2013a; Conley & Krahenbuhl, 1980; Daniels, 1985; Daniels & Daniels, 1992) and to enhance to ecological validity of the study, we adopted a novel design previously reported by Vandenbogaerde, Hopkins and Pyne (2012) to investigate the effects of our intervention on actual competition performance (Vandenbogaerde et al., 2012). Interestingly, our data revealed distinct differences between the prescribed training regimes in terms of performance gains and physiological adaptations, and an apparent gender-specific response to resistance training. For example, there were substantial beneficial mean effects on competition performance for the female training groups compared to controls ($-1.2 \pm 1.3\%$), whereas resistance training for males proved to be possibly harmful ($0.5 \pm 1.2\%$). This observation could have been an indication that endurance-trained female athletes may have a greater requirement in terms of resistance training maintenance (Peterson et al., 2011), whereas for males this training might be beneficial only during the pre-season or build-up phase of training when there is less emphasis on competition and gains can be made in physiological measures without the risk of harm to competition performance. The differences in effects

between men and women could have also been due in part to differences in training intensity and competition distance. The proportion of training that occurred at $\geq 80\%$ VO_2max for females was moderately higher than that for males (Table 12), which might have translated into performance enhancement over the women's shorter race distance (5-6 km vs. 8-10 km for the men).

When comparing the two modes of resistance training we were surprised to find that the combined plyometric and resistance training (PRT) was inferior to heavy resistance training (HRT) alone in both genders. Overall, PRT resulted in greater harm to competition times (slower run times) by $0.8\% \pm 1.5\%$ compared to only $0.1\% \pm 1.3\%$ harm in HRT for male competition performance. Similarly, in females, PRT improved competition times by $-1.1\% \pm 1.3\%$ compared to $-1.4\% \pm 1.4\%$ in the HRT group. Predictably, changes in physiological measures related to distance running performance were consistent with performance data, indicating greater improvements (or less decrements in the case of men) following HRT than matched volume-load PRT. We observed a substantial increase in laboratory-derived peak running speed following HRT (4.6% and 4.4% in men and women respectively) compared to PRT (1.0% and 2.2% in men and women respectively). Previous research has shown peak running speed to be a good indicator of endurance performance in middle- and long-distance running events (Billat & Koralsztein, 1996; Noakes, 1988; Noakes et al., 1990; Saunders et al., 2010; Stratton et al., 2009) and Noakes (Noakes, 1988; Noakes et al., 1990) has suggested that peak running speed could be used as a measure of the 'muscle power' factor in endurance runners. Additionally, HRT improved running economy by 1.7% and 3.4% in males and females respectively, while PRT only improved running economy by 0.2% and 1.0%. Although both HRT and PRT results were in accordance with growing literature demonstrating that heavy resistance-training or plyometric training improved the running economy of well-trained athletes ((Guglielmo et al., 2009; Johnston et al., 1997; Millet et al., 2002; Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Storen et al., 2008; Turner et al., 2003), the magnitude of enhancements were lower in our study compared to previous studies reporting effects following heavy-resistance (Guglielmo et al., 2009; Johnston et al., 1997; Millet et al., 2002; Storen et al., 2008) or plyometric training (Paavolainen, Hakkinen, et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Turner et al., 2003). This could be due to different phases of season that the studies were performed. Regardless, in both HRT and PRT, improvements in running economy occurred in the absence of any substantial change in VO_2max suggesting that improved running economy was a result of neuromuscular characteristics rather than improved cardiorespiratory fitness.

Indeed, we observed small to moderate increases in leg stiffness in the male (15.0%; $\pm 11.5\%$) and female HRT (11.5%; $\pm 6.9\%$) groups and PRT training was associated with moderate negative effects on leg stiffness compared to HRT (males -15.7%; $\pm 15.2\%$; -6.3%; $\pm 8.9\%$). One of the most important roles of the muscle during running is to modulate leg stiffness and storage-recoil of energy. The conversion of energy to motion involves recoil of some elastic energy in muscle and tendon, thus a “stiffer” muscle or tendon would be better at transferring energy economically or without the need for additional oxygen consumption (Cavagna & Kaneko, 1977; Dalleau et al., 1998; Spurr et al., 2003). Indeed, previous evidence has shown a negative correlation between leg stiffness and cost of running (Albracht & Arampatzis, 2006; Arampatzis et al., 2006). Kerdok et al. (2002) have shown changes in both muscle-tendon stiffness and running economy when manipulating the running surface (Kerdok et al., 2002), indicating that runners adjust the level of leg stiffness towards the most optimal degree, to maintain consistent running mechanics on different surfaces. This could be important, particularly in cross-country runners like those in this study where competitions often take place on a variety of undulating surfaces in a single competition.

8.2 Practical Applications

The overall aim of this thesis was to examine the relative efficacy of different forms of movement-specific resistance exercise to improve running economy and performance in trained distance runners. To this end, this thesis examined several ‘novel’ movement-specific resistance exercises through a series of investigations structured progressively, utilizing a range of experimental designs. Based on our findings, a summary of practical applications to assist coaches, sport scientists and distance runners to understand how to improve running economy and performance are made in the following section as well as the contribution to sports theory.

While many lower body characteristics commonly measured during laboratory or field training sessions represent specific or independent qualities of running economy that can be assessed and trained independently, it is recommended that for coaches and athletes trying to enhance running economy that a greater efficiency of training can be achieved by targeting interventions that increase lower-body stiffness. Furthermore, while the Achilles moment arm length is a non-modifiable determinant related to running economy, this measure appears to provide the practitioner with information about the stiffness of the lower body which may elucidate an athlete’s potential to improve their running economy; however, more data is needed to validate this.

To optimize the warm-up activities of distance runners prior to competition, it is recommended the addition of a weighted-vest to specific pre-competition activities. For the specific purpose of enhancing lower-body stiffness, running economy and/or performance we recommend the addition of a weighted vest equivalent to approximately 20% of the athletes body mass during pre-competition strides. However, because the weighted-vest appears to have a negative effect on perceived race readiness in first-time users, it is recommended using the weighted vest in training prior to use before competition.

The findings from Chapter 6 provide support for incorporating uphill interval running in the training programs of distance runners to improve various physiological, biomechanical and neuromuscular parameters relevant to running performance. Different uphill training approaches appear to induce specific physiological and mechanical adaptations, which suggests that hill training should be carefully matched to the strengths and weaknesses of the athlete, the underlying demands of the event and the training or competitive focus. Specifically, it is recommended enhancing running economy by including short 10 to 20-s sprints uphill on a steep (15-20%) gradient with a walk/jog recovery (60-120-s) back down the hill into the training of middle- and long-distance runners. It is suggested the same loading parameters to enhance stride rate, lower-body stiffness and other neuromuscular characteristics as well. To optimize the enhancement of maximal aerobic capacity and lactate threshold, it is recommended to include 2.5 to 4-min bouts of uphill running at approximately 95% $v\dot{V}O_2\text{max}$ on a gradual 7-8% gradient. Unfortunately, until more data are obtained, runners can assume that performance enhancements can be made as a result of changes in a variety of mechanistic variables caused by varying the uphill running loading parameters since every participant in this study demonstrated some sort of improvement in 5-km time-trial performance.

It is recommended that coaches of female distance runners consider the addition of heavy-resistance training or the combination of heavy-resistance and plyometric resistance training to their training regimen during the competition phase of a cross-country season. However, when considering the two treatments, it is recommended for females they perform heavy-resistance training over the combination of plyometric and heavy resistance training because the combination resistance training was harmful to cross-country competition performance and most laboratory-based measures when compared to a matched volume-load heavy resistance-training program. Furthermore, it is recommended that males may want to implement such

training in-season with caution until more research establishes characteristics of positive or negative responders.

At the outset of this thesis, the theoretical underpinning of factors affecting running economy (Figure 3) and various strategies to improve running economy (Figure 6) was presented in Chapters 2 and 3 based upon the state of knowledge at the time. Previously, information regarding factors affecting running economy had been presented across a range of review and original research articles. However, here I present the first comprehensive theoretical model of factors affecting running economy (Figure 15) based upon both previous and present evidence.

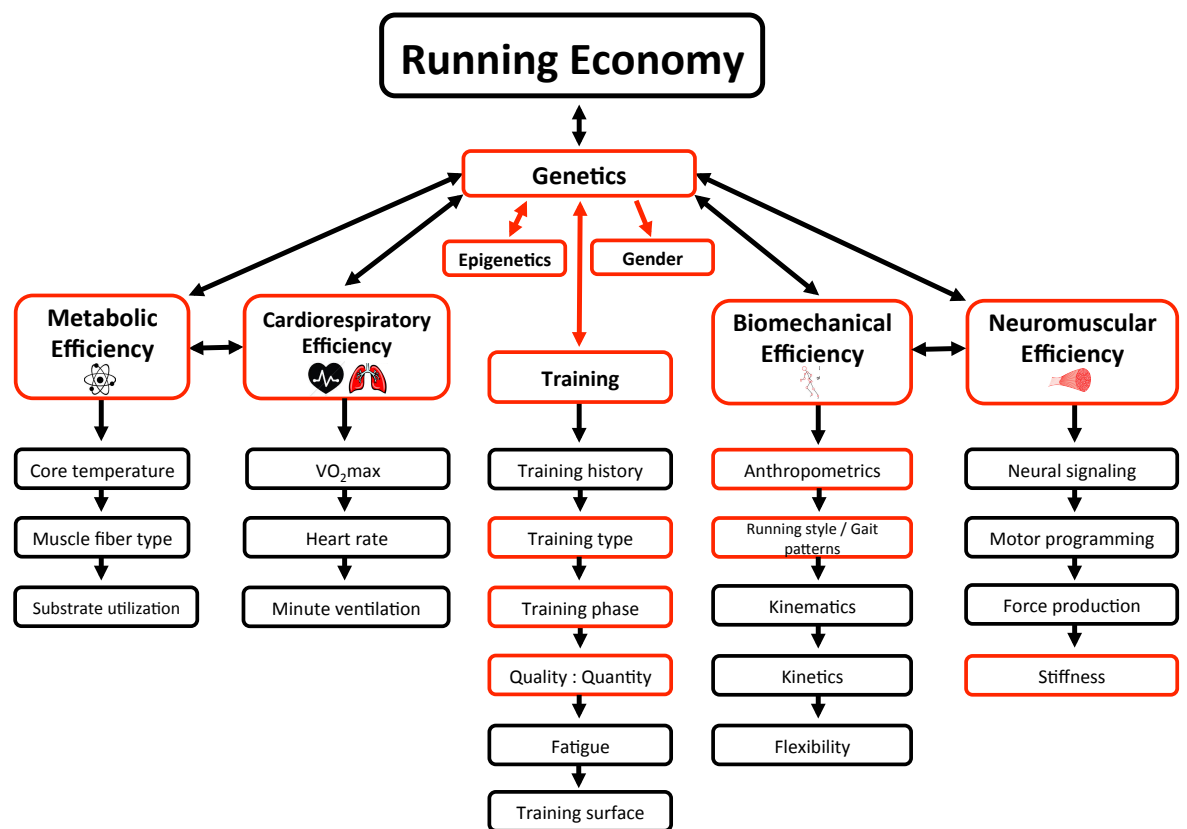


Figure 15: Factors affecting running economy following contribution from this thesis (red indicates contribution from this thesis).

It appears that while the measurement of running economy is represented by the energy demand for a given velocity of submaximal running and expressed as the submaximal VO_2 at a given running velocity, this VO_2 reflects the combined functioning of heritable traits related to the metabolic, cardiopulmonary, biomechanical and neuromuscular systems as well as training related factors. While many of these factors had been presented previously in many different research and review articles (black boxes in Figure 15), many of these factors had yet to be considered, discussed, or

presented as I have in this thesis (red boxes in Figure 15). Specifically, the heritability of genetic traits no doubt is the prevailing factor affecting running economy, however at the moment, there is limited research examining specific genotypes related to better economy (He et al., 2007; Rodas et al., 1998). Furthermore, several studies have discussed the dominance of East African distance runners being related to their exceptional running economy (Lucia et al., 2006; Lucia, Moran, Zihong, & Ruiz, 2010; Lucia et al., 2008) which potentially has an epigenetic component to it, however, more research is needed in this area as well. Furthermore, differences in running economy that exist between male and female athletes was also a consideration. Why these differences exist has yet to be fully elucidated. However, I did attempt to present normative values of running economy ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) for male and female runners (Table 2) based on previous and present cross-sectional data, which has yet to be presented in the literature, but will provide practitioners with relative VO_2 values for athletes at a range of ability levels. These differences in running economy to some extent are related to a number of training related factors also affect running economy, which were considered. Lastly, attention of the metabolic, cardiopulmonary, biomechanical and neuromuscular systems working together as a whole to make the measurement of running economy is a novel contribution to this theoretical model of running economy. Previous research has considered these systems independent of one another (Anderson, 1996; Bonacci et al., 2009; Daniels, 1985; Saunders, Pyne, et al., 2004a) however, it has been overlooked that it is possible to become more efficient in one area yet have total running economy be negatively affected because of a larger decrease in another aspect of efficiency.

Furthermore, at the beginning of this thesis, there was relatively little literature regarding strategies to improve running economy (Figure 6); however, over the course my thesis, the body of literature related to this topic increased substantially in size. Therefore, an updated model of strategies to improve running economy (Figure 16) that this thesis and other research have contributed to is presented. Some of these training or passive strategies have been previously examined or discussed (black text in Figure 16) in the literature such as stretching, training environment, or even various resistance training modalities. However, here I have presented many of these strategies in an updated more comprehensive way after my own experimentation of several strategies to improve running economy (Chapter 5,6 and 7) as well as reviewing all of the literature (Chapter 3) (red text in Figure 16).



Figure 16: Schematic of strategies to improve running economy following contribution from this thesis (red indicates contribution from this thesis).

This thesis presented several novel strategies to improve running economy never before considered in the literature. Based upon my research the inclusion of short (10-20 s) uphill sprints (Chap 6) as well as heavy resistance training (Chap 7) into the training programs of athletes is recommended. Additionally, the use of a weighted vest during the warm-up procedures prior to competition to improve running economy and subsequently performance is a unique contribution to sport, however, the specific prescription of these training methods requires further attention (see Recommendations of future research below). Other new theoretical ideas and summary of recent published literature examining strategies to enhance running economy, such as various nutritional interventions, acute muscle conditioning, heavy resistance training and plyometric training and the interaction between these two modalities, as well as training type, history and environment have been discussed (Chapter 3) and presented in Figure 16.

8.3 Thesis limitations

It is acknowledged that despite the positive findings of this thesis, there were some limitations that should be considered, specifically:

- In study 3 (Chapter 6), we adopted a unique experimental design, first adopted by Stepto et al. (1999) to determine to determine the most effective uphill interval-training protocol on running economy and performance in well-trained distance runners (Stepto et al., 1999). While initial modelling suggested 20 subjects would be a sufficient sample size, and confidence intervals were derived for each measure by bootstrapping, it is possible that obtaining more trained runners would have improved chances of establishing a clear optima for performance measures.
- The error of measurement for neuromuscular measures estimated in Chapter 6 adds some uncertainty to the true relationship between training interventions and effect (for Chapter 4-7 because all neuromuscular measures were evaluated using the same methodology equipment) but is not unreasonable, given that the measured error is population specific and is still comparable to other reliability studies (Cormack et al., 2008).
- While, the perceived race readiness scale used in Chapter 5 prior to each subject's performance trial has not been validated, it has been used previously by Ingham et al. (2013) (Ingham et al., 2013).
- Endurance performance in Chapter 5 was measured by peak running speed in an incremental test, rather than performance time trials. Although changes in peak power tests such as peak running speed are highly correlated with changes in endurance performance (Hopkins et al., 2001), the changes in peak running speed observed may not cause an equal change in real life endurance performance.
- To analyze potential mechanisms underlying the effect of training on performance in Chapter 6, changes in performance were plotted against changes in physiological and other measures and the scatterplots inspected for any linear trend. A clear linear trend in the graph would have allowed for estimation of the smallest important change in the mechanism variable as the change that tracked the smallest important change in performance. However, there were no such clear linear relationships, presumably because random error of measurement masked any relationship between real individual differences in changes in performance and the mechanism variable. Therefore, a different approach to estimating smallest changes was adopted. The enhancement in performance turned out to be practically constant across the range of training intensities (~2%). Therefore, to estimate the smallest

important change in each mechanism variable, we assumed that the tracking of changes in the means of the mechanism and performance variables reflected the underlying relationship in the individual change scores.

While this thesis has demonstrated substantial outcomes that further broaden the body of knowledge surrounding the various strategies to improve running economy, the results need to be interpreted with caution given the aforementioned thesis limitations.

8.4 Recommendations for future research

This thesis examined the influence of various strategies to improve running economy and performance. While it has addressed a number of questions specific to this area, further research addressing the following issues is warranted:

- Wherever possible “elite” athletes should be used for future studies since previous meta-analyses has clearly shown that performance adaptations between elites and sub-elite athletes are of a differing magnitude. It is likely that any intervention that facilitates changes in elite athletes will likely also affect highly-trained and moderately trained athletes.
- Whenever possible, direct measures of neuromuscular activity should be examined to determine their relationship and effect on running economy following training.
- In Study 1 (Chapter 4) it was demonstrated that Achilles moment arm length is a non-modifiable factor that appears to be very largely correlated with running economy; future research should aim to elucidate why some athletes have good or poor economy as well as if this lower-limb characteristic sets upper and lower limits of an individual’s ability to improve their running economy. This information may help with talent identification as well as explain why some athletes may be non-responders to specific training regimens.
- Leg stiffness appears to be highly correlated to running economy; therefore, future studies should aim to determine the trainability of leg stiffness across varying interventions and levels of fitness.
- In Study 2 (Chapter 5) it was demonstrated that strides with a weighted-vest have a priming effect on leg stiffness and running economy, which subsequently had a major effect on peak treadmill running speed. Enhancing this study to further investigate how to optimize the use of weighted vests in warm-up

procedures (e.g. variations in loading parameters) to enhance subsequent running performance. Little is known about such priming exercise for endurance performance therefore this information may aid athletes in preparation for competitions.

- The results from Study 3 (Chapter 6) showed there was no clear optimum of uphill interval training for 5-km time-trial performance but the highest intensity was clearly optimal for running economy. Further studies are required to establish whether improvements derived from uphill interval training can be established through variations in the frequency, duration, volume and periodization of training.
- Study 4 (Chapter 7) was the first to investigate the effects of two resistance-training interventions on actual competition performance. Further studies are required to investigate the effects of various resistance training interventions during the competition phase of cross-country and track & field seasons and the effects on actual competition performance.

8.5 Conclusions

In summary, the findings from this thesis have demonstrated that runners can improve their running economy through a variety of resistance exercises. This was seen following both acute and short-term (6-12 weeks) interventions. Study one identified several lower-body determinants of running economy that could explain difference or changes following training. Specifically increased leg stiffness and shorter Achilles moment arm length were identified as determinants of running economy. For the first time in the literature this study also showed that leg stiffness was related to the length of the moment arm of the Achilles tendon. Several other variables were small to moderately related to running economy suggesting that running economy is likely determined from the sum of influences from multiple lower-body attributes. Study two for the first time demonstrated that high-intensity running with an added load as part of an athlete's warm-up routine enhances subsequent performance in well-trained runners. The regression analysis suggested that the increases in leg stiffness following weighted vest strides were responsible for the improved performance, however, the weighted-vest warm-up routine also elicited a 6.0% improvement in running economy; which, other things being equal, would result in a ~6% enhancement in performance according to the model of di Prampero et al. (1993) (di Prampero et al., 1993).

The findings of study three support anecdotal reports for incorporating uphill interval training in the training programs of distance runners to improve physiological parameters relevant to running performance. Specifically we observed that training at the highest intensities (shortest duration and highest gradient) was associated with the greatest improvements in running economy and neuromuscular characteristics as well as increased stride rate. Overall, it appears that different uphill training approaches appear to induce specific physiological and mechanical adaptations, which suggests that hill training should be carefully matched to the strengths and weaknesses of the athlete, the underlying demands of the event and the training or competitive focus. Study four revealed that the addition of heavy resistance training or plyometric resistance training to the in season training of female cross-country runners was beneficial to competition performance, while both treatments were possibly harmful to male competition performance. However, when the two resistance training treatments were compared, the addition of plyometric resistance training to heavy resistance training was harmful to cross-country competition performance and most laboratory-based measures. The greater improvements in competition performance were accompanied by an enhancement in running economy and peak running speed following heavy resistance training, compared to plyometric resistance training, probably a result of improvements in lower limb strength, leg stiffness and utilization of stored elastic energy.

Overall, it can be concluded that a variety of strategies can be implemented into the training of distance runners to improve running economy. Furthermore, improvements in running economy appear to be modulated through enhancements in lower-body stiffness. Moreover, it appears that the improvements in running economy following various training strategies presented in the thesis contribute to improved running performance.

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APPENDICES

Appendix 1: Auckland University of Technology Ethics Committee Approval Memos



MEMORANDUM

Auckland University of Technology Ethics Committee (AUTEC)

To: Andrew Kilding
From: **Charles Grinter** Ethics Coordinator
Date: 3 August 2010
Subject: Ethics Application Number 10/160 **Strategies to improve running economy in New Zealand triathletes and runners.**

Tena koe Andrew

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 12 July 2010 and that I have approved your ethics application. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 13 September 2010.

Your ethics application is approved for a period of three years until 3 August 2013.

I advise that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/research/research-ethics/ethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 3 August 2013;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/research/research-ethics/ethics>. This report is to be submitted either when the approval expires on 3 August 2013 or on completion of the project, whichever comes sooner;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact me, by email at ethics@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the AUTEC and myself, I wish you success with your research and look forward to reading about it in your reports.

On behalf of Madeline Banda, Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Kyle Barnes kyle.barnes@aut.ac.nz, Andrew Kilding, Paul Laursen

9 July 2013

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Re Ethics Application: **13/153 Effects of warm up with weighted vest on running economy and peak speed.**

Thank you for providing evidence as requested, which satisfies the points raised by the AUT University Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 8 July 2016.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/researchethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 8 July 2016;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/researchethics>. This report is to be submitted either when the approval expires on 8 July 2016 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

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

All the very best with your research,



Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Kyle Barnes kyle.barnes@yahoo.com

Appendix 2: Hope College Human Subjects Review Board Ethics Approval Memo



HOPE COLLEGE

DEPARTMENT OF COMMUNICATION

August 10, 2011

Professor Mark Northuis
Department of Kinesiology
Hope College

Kyle Barnes
Sport Performance Research Institute
School of Sport and Recreation
AUT University, Auckland, NZ

Dear Mark & Kyle:

Your research proposal, "A Competition-Based Research Design to Assess a Resistance Training Intervention Affecting the Performance and Running Economy of Cross Country Runners," has been approved by the HSRB. Thank you for submitting the revised application that addresses the HSRB concerns or requests for clarification (in response to HSRB letter dated 8/9/11).

This approval is for a 12-month period from the date of this letter, and is for Mark Northuis to act as supervisor for this research project for all data collected on Hope College's campus or with Hope College student participants.

If your research should continue beyond this 12-month period, you will need to file a continuation request. Please see the HSRB website (www.hope.edu/admin/hsrb) for the necessary procedures for requesting a continuation of your HSRB approval beyond one year.

It is also important that you notify HSRB of any changes to your research protocol, or any unanticipated risks or effects of your project on human participants. Please see the HSRB website for procedures for requesting modifications of this research project. If there are any concerns about participants' physical or mental wellbeing, the security of participants' information, or any unanticipated risks experienced by your participants, please contact HSRB immediately by email: hsrb@hope.edu.

Your proposal, all correspondence with HSRB, and this HSRB decision letter will be electronically archived. Please also keep this letter for your records.

Thank you for your diligence in providing a safe and secure environment for human participants in research projects at Hope College. Best wishes with your research.

Deirdre D. Johnston
HSRB Chair
johnston@hope.edu

MARTHA MILLER CENTER FOR GLOBAL COMMUNICATION / 257 COLUMBIA AVENUE / PO BOX
9000
HOLLAND, MICHIGAN 49422-9000 / 616-395-7595 / FAX 616-395-7937

Participant Information Sheet



Date Information Sheet Produced:

14th September 2010

Project Title

Lower Limb Determinants of Running Economy in Male and Female Runners

An Invitation

Hi, my name is Kyle Barnes and I am a PhD student at AUT University. In affiliation with Triathlon New Zealand and Athletics New Zealand; along with my supervisors Dr. Andrew Kilding, Dr. Will Hopkins, and Dr. Mike McGuigan, I am inviting you to help with a project that is investigating the lower limb determinants of running economy in male and female runners.

Before you decide, please read the information below to find out more of what this project is all about. After which, you need to decide whether or not you would like to be involved. You don't have to be involved, and you can stop being involved in the study at any time.

What is the purpose of this research?

Even though we've known about its importance for about 80 years, running economy has been largely ignored by researchers, coaches and athletes until recently, when we figured out that RE is a better predictor of performance than other more commonly used measures. For example, we regularly measure the maximum volume of oxygen that can be used (i.e. VO_{2max}), but for running events longer than about 5000 m, runners don't use this "maximum" amount, as such events are sub-maximal. Therefore, a more important measure becomes the volume of oxygen that is used when the athlete is running at a sub-maximal speed.

Despite the performance benefits of being an economical runner, researchers have yet to resolve why some runners demonstrate markedly better economy when compared to counterparts exhibiting similar fitness, training history and performance backgrounds. A number of physiological, biomechanical and neuromuscular factors appear to influence running economy in well-trained or elite runners. These include metabolic adaptations within the muscle such as increased mitochondria and oxidative enzymes, more efficient mechanics leading to less energy wasted on braking forces and excessive vertical oscillation, and the ability of muscles to store and release elastic energy by increasing the lower-limb stiffness. Furthermore, a variety of modifiable (e.g. percent body fat, body mass) and un-modifiable (e.g. Achilles moment arm length, height, skeletal structure) anthropometric measures influence biomechanical and neuromuscular efficiency and subsequently alter running economy. For example, the amount of energy stored in a tendon depends on the mechanical properties of the tendon and on the force that stretch the tendon. Thus, for a given movement pattern, tendon force is inversely related to the moment arm of the Achilles tendon. Since it is generally accepted that storage and reutilization of elastic energy in tendons substantially reduces energy demands in running previous research has been able to establish a

relationship between the variation in running economy and the moment arm of the Achilles tendon. Recent research has focused on various neuromuscular or biomechanical characteristics as mechanisms to explain improvements in running economy. Any lower-limb adaptations which allows for improved muscle power development, enhanced ability of the muscles to store and release elastic energy by increasing stiffness, or more efficient mechanics characterized by more skilled control of movement and muscle recruitment patterns could certainly explain differences in running economy among runners. The differences in running economy that exist between males and females has been previously investigated, but with mixed findings. Research has yet to explore whether many of these lower-limb characteristics can explain these inter-individual differences in running economy between male and female trained distance runners. Such data would allow practitioners to assess and train specific qualities of running economy throughout various training phases. Therefore, the present study was designed to evaluate the lower-limb determinants of running economy among well-trained male and female distance runners.

How was I chosen for this invitation?

You are a competitive senior runner (18+ years of age) in the Auckland region who competes regularly in local and national competitions.

What will happen in this research?

If you decide to participate in this research you will be required to come to the SPRINZ labs at AUT-Millennium on one occasion to participate in a range of laboratory-based physiological and biomechanical assessments. During your visit you will be measured for a variety of anthropometric characteristics (height, weight, and body composition) will be measured using scales, tape measures and skin fold callipers and camera. Following this you will complete a treadmill test to assess your running economy and VO_2 max. The running economy test will involve you running at 5 to 7 submaximal speeds for 4 minutes each with 90 seconds recovery followed by a VO_2 max test which involves you running at the last submaximal speed completed with a progressively increasing gradient until volitional exhaustion. Lastly, you will complete several jumping tests that measure strength and power.

What are the discomforts and risks?

There are several maximal assessments as part of this research. It is expected that you will experience temporary discomfort during maximal exertion during various run assessments. These tests are used to measure your maximal aerobic capacity and performance capabilities. The amount of exertion at the conclusion of the assessments will be similar to what you will feel at the end of a 5 km or 10 km race. You will be able to interrupt any of the tests if you feel uncomfortable at any time.

How will these discomforts and risks be alleviated?

During the maximal assessments there will be lab attendants present who will be able to assist if you are feeling unwell. A medical facility is located on campus with medical doctors and nurses and other qualified medical staff. Additionally, Kyle Barnes is qualified instructor for the American Red Cross in CPR, First Aid and AED emergency care.

What are the benefits?

You will benefit from this research through having a better understanding of your personal physiological and biomechanical characteristics (VO_2 max, Lactate Threshold, Running Economy, Heart Rate, Training Zones, etc.).

What compensation is available for injury or negligence?

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

How will my privacy be protected?

All information related to you will be coded in order to ensure that you cannot be identified. Data will be stored on a memory stick or CD and stored in the SPRINZ secure Ethics and Data facility at AUT Millennium campus and all hard copy and electronic data will be destroyed after six years and will only be accessible to the people of the running economy project. No-one will be able to identify you from any of the summary findings for the report of the project. Information regarding your results will only be passed onto others with your permission.

What are the costs of participating in this research?

There are no costs to participating in this research.

What opportunity do I have to consider this invitation?

- You may take the time you need and decide whether or not you would like to be involved.
- You can stop being involved in the project at any point.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to myself.

Will I receive feedback on the results of this research?

Yes, individual feedback will be provided to you, if you request it. The group results will be used in scientific journal articles and conference presentations. Media articles may be written based on the results of the present study.

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

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

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7076, Andrew.kilding@aut.ac.nz

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

Whom do I contact for further information about this research?

Researcher Contact Details:

Kyle Barnes, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Auckland 0637, Ph 022 655 4685, kyle.barnes@yahoo.com

Project Supervisor Contact Details:

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7056, Andrew.kilding@aut.ac.nz

Participant Information Sheet



Date Information Sheet Produced:

28th May 2013

Project Title

Effects of Warm Up with Weighted Vest on Running Economy and Peak Speed

An Invitation

Hi, my name is Kyle Barnes and I am a PhD student at AUT University. In affiliation with Sport Performance Research Institute New Zealand; along with my supervisors Dr. Andrew Kilding, Dr. Will Hopkins and Dr. Mike McGuigan, I am inviting you to help with a project that is investigating the effects of a warm-up with a weighted vest on running economy and peak running speed.

Before you decide, please read the information below to find out more of what this project is all about. After which, you need to decide whether or not you would like to be involved. You don't have to be involved, and you can stop being involved in the study at any time.

What is the purpose of this research?

Even though we've known about its importance for about 80 years, running economy (RE) has been largely ignored by researchers, coaches and athletes until recently, when we figured out that RE is a better predictor of performance than other more commonly used measures. For example, we regularly measure the maximum volume of oxygen that can be used (i.e. VO_{2max}), but for running events longer than about 5000-m, runners don't use this "maximum" amount, as such events are sub-maximal. Therefore, a more important measure becomes the volume of oxygen that is used when the athlete is running at a sub-maximal speed. Given the importance of RE for endurance performance, successful training interventions that improve RE and ultimately performance would likely be embraced by coaches and athletes. Various resistance-training approaches are currently prescribed by coaches and strength & conditioners. However, little information is available pertaining to the optimal type of resistance exercise that maximizes improvements in RE and performance. To this end, the purpose of this research is twofold:

1. Determine the effects of using sport specific hypergravity warm-up on neuromuscular and metabolic mediators related to endurance performance.
2. To determine efficacy of using a set of "strides" (sprints) with a weighted vest during a traditional warm-up on endurance performance.

How was I chosen for this invitation?

You are a senior member (18+ years of age) of the Takapuna Harriers Athletic Club who competes regularly in local and national competitions contacted through the Takapuna Harriers mailing list or newsletter or personally contacted by the principle researcher.

What will happen in this research?

If you decide to participate in this research you will be required to come to the SPRINZ labs at AUT-Millennium a total of three times for research testing. Following a familiarisation session during which you will be introduced to all equipment and procedures, each subsequent test will involve you performing a standardized warm-up, which will consist of 15-20 minutes of easy running while measuring VO_2 , followed by a series of 'strides' with a weighted vest (at 20% body weight) or at normal body weight. To measure VO_2 you will wear a mouthpiece, similar to a swimming snorkel. This will be followed by another 5 min of easy run while measuring VO_2 which will continue directly into a peak speed test in which the treadmill speed will increase one kilometre per hour every minute until volitional exhaustion.

What are the discomforts and risks?

There are several maximal assessments as part of this research. It is expected that you will experience temporary discomfort during maximal exertion during various run assessments. These tests are used to measure your maximal aerobic capacity and performance capabilities. The amount of exertion at the conclusion of the assessments will be similar to what you will feel at the end of a 5 km or 10 km race. You will be able to interrupt any of the tests if you feel uncomfortable at any time.

How will these discomforts and risks be alleviated?

During the maximal assessments there will be lab attendants present who will be able to assist if you are feeling unwell. A medical facility is located on campus with medical doctors and nurses and other qualified medical staff. Additionally, Kyle Barnes is qualified instructor for the American Red Cross in CPR, First Aid and AED emergency care.

What are the benefits?

You will benefit from this research through having a better understanding of your personal physiological and biomechanical characteristics (VO_2 max, Lactate Threshold, Running Economy, Heart Rate, etc.) as well as (hopefully) becoming more economical through the assigned training intervention group which will ultimately lead to better performances.

What compensation is available for injury or negligence?

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

How will my privacy be protected?

All information related to you will be coded in order to ensure that you cannot be identified. Data will be stored on a memory stick or CD and stored in the SPRINZ secure Ethics and Data facility at AUT Millennium campus and all hard copy and electronic data will be destroyed after six years and will only be accessible to the people of the running economy project. No-one will be able to identify you from any of the summary findings for the report of the project. Information regarding your results will only be passed onto others with your permission.

What are the costs of participating in this research?

There are no costs to participating in this research.

What opportunity do I have to consider this invitation?

- You may take the time you need and decide whether or not you would like to be involved.
- You can stop being involved in the project at any point.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to myself.

Will I receive feedback on the results of this research?

Yes, individual feedback will be provided to you, if you request it. The group results will be used in scientific journal articles and conference presentations. Media articles may be written based on the results of the present study.

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

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

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7076, Andrew.kilding@aut.ac.nz

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

Whom do I contact for further information about this research?

Researcher Contact Details:

Kyle Barnes, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Auckland 0637, Ph 022 655 4685, kyle.barnes@yahoo.com

Project Supervisor Contact Details:

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7056, Andrew.kilding@aut.ac.nz

Participant Information Sheet



Date Information Sheet Produced:

21st June, 2010

Project Title

Uphill Running Training Methods to Enhance Running Economy in New Zealand Triathletes and Runners

An Invitation

Hi, my name is Kyle Barnes and I am a PhD student at AUT University. In affiliation with Triathlon New Zealand and Athletics New Zealand; along with my supervisors Dr. Andrew Kilding, Dr. Paul Laursen, and Dr. Mike McGuigan, I am inviting you to help with a project that is investigating optimal resistance training methods to improve running economy and performance in runners and triathletes.

Before you decide, please read the information below to find out more of what this project is all about. After which, you need to decide whether or not you would like to be involved. You don't have to be involved, and you can stop being involved in the study at any time.

What is the purpose of this research?

Even though we've known about its importance for about 80 years, running economy (RE) has been largely ignored by researchers, coaches and athletes until recently, when we figured out that RE is a better predictor of performance than other more commonly used measures. For example, we regularly measure the maximum volume of oxygen that can be used (i.e. VO_2max), but for running events longer than about 5000 m, runners don't use this "maximum" amount, as such events are sub-maximal. Therefore, a more important measure becomes the volume of oxygen that is used when the athlete is running at a sub-maximal speed. Given the importance of RE for endurance performance, successful training interventions that improve RE and ultimately performance would likely be embraced by coaches and athletes. Many athletes incorporate hill running as a sport-specific/functional form of resistance training. However, there is mixed opinion amongst coaches on whether hills should be 'short and steep' or 'long and gradual'. To our knowledge, no research exists on how various hill training methods affect RE, strength, power, and other performance measures. To this end, the purpose of this research is threefold:

1. Determine the hill training is effective at improving running economy
2. Identify the optimal hill training approach
3. Determine biomechanical and physiological factors affecting RE in well-trained runners and triathletes

How was I chosen for this invitation?

You are part of Triathlon New Zealand's High Performance squad or recognised as a national class triathlete.

What will happen in this research?

If you decide to participate in this research you will be required to come to the University lab at the Millennium Institute for Sport and Health in Mairangi Bay a total of six times for research testing (three before and three after the intervention) as well as an additional **18** times for the intervention group you are assigned to. The first day of pre-intervention testing will take approximately 90 minutes, the second day will take 120 minutes and the third day will involve 90 minutes of your time. You will be asked to participate in a range of laboratory-based physiological and biomechanical assessments over a 7 day period. Two days rest is scheduled between each assessment day. The same time frame should be expected for post-intervention testing. Each training session throughout the training intervention period will last approximately 60 minutes.

On the first day anthropometric variables (height, weight, limb length, circumference and skinfold) will be measured using scales, tape measures and skinfold callipers. Following this you will complete a treadmill test to assess your running economy and VO_2 max. The RE test will involve you running at 4 to 6 submaximal speeds for 4 minutes each with 90 seconds recovery followed by a VO_2 max test which involves you running at the last submaximal speed completed with a progressively increasing gradient until volitional exhaustion. The second day of testing involves similar anthropometric measurements followed by a RE test identical to day 1 that will simply be preceded by a 45 minute high intensity cycling bout designed to replicate the cycling portion of a draft legal triathlon. After approximately 20 min of recovery a maximal anaerobic running test (MART) will be completed. The MART consists of a series of 20-s runs on a treadmill at progressively faster speeds until volitional exhaustion. On the third day of testing after a warm-up you will complete two jumping tests that measure strength and power followed by a 5 km time-trial on an outdoor 400 m running track. After the 5 km time-trial you will complete the same jumping tests as before the time-trial as well as a maximal strength test on the squat and bench press. Additionally, during each running tests on each day, you will be video recorded for biomechanical analysis of running form.

During the intervention period will be assigned to one of the various training intervention groups and follow a periodised set of resistance training exercises deemed appropriate by Triathlon New Zealand's Strength and Condition coach as well as NZASNI strength and power scientists. The intervention period will last 54 days or six 9-day training cycles. Additionally, you will be asked to keep a detailed record of your training which will include details such as load, intensity, and volume of training from swimming, cycling, and running.

The same tests performed before the intervention will be performed after in the same order.

What are the discomforts and risks?

There are several maximal assessments as part of this research. It is expected that you will experience temporary discomfort during maximal exertion during various run assessments. These tests are used to measure your maximal aerobic capacity and performance capabilities. The amount of exertion at the conclusion of the assessments will be similar to what you will feel at the end of a 5 km or 10 km race. You will be able to interrupt any of the tests if you feel uncomfortable at any time.

How will these discomforts and risks be alleviated?

During the maximal assessments there will be lab attendants present who will be able to assist if you are feeling unwell. A medical facility is located within the facility with medical doctors and other qualified medical staff. Additionally, Kyle Barnes is qualified instructor for the American Red Cross in CPR, First Aid and AED emergency care.

What are the benefits?

You will benefit from this research through having a better understanding of your personal physiological and biomechanical characteristics (VO₂max, Lactate Threshold, Running Economy, Heart Rate, etc.) as well as (hopefully) becoming more economical through the assigned training intervention group which will ultimately lead to better performances.

What compensation is available for injury or negligence?

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

How will my privacy be protected?

All information related to you will be coded in order to ensure that you cannot be identified. The information will remain in locked storage and will only be accessible to the people of the running economy project. No-one will be able to identify you from any of the summary findings for the report of the project. Information regarding your results will only be passed onto others with your permission.

What are the costs of participating in this research?

The duration of the first day of testing will last approximately 90 minutes (10 minutes for consent forms and clarification of study protocols, 20 minutes for anthropometry, 60 minutes for the Running Economy and VO₂max test). The second day of testing will last approximately 120 minutes (10 minutes for anthropometry, 75 minutes for Running Economy off the Bike test and 15 minutes for the MART test). Day three testing will last approximately 90 minutes in duration (45 minutes for the 5 km time-trial and 45 minutes for power and strength assessments).

Each training session throughout the training intervention period will last approximately 60 minutes. Because the subjects in these studies train in 9 day cycles, each subject will have 3 x 60 min sessions every 9 day cycle (6 total cycles x 3 training sessions per cycle = 18 total training sessions)

We will provide you with a \$20 petrol voucher to help cover costs of transport to the testing sessions.

What opportunity do I have to consider this invitation?

- You may take the time you need and decide whether or not you would like to be involved
- You can stop being involved in the project at any point.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to myself.

Will I receive feedback on the results of this research?

Yes, individual feedback will be provided to you, if you request it. The group results will be used in scientific journal articles and conference presentations. Media articles may be written based on the results of the present study.

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

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

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7076, Andrew.kilding@aut.ac.nz

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEK, Madeline Banda, madeline.banda@aut.ac.nz, Ph 921 9999 ext 8044.

Whom do I contact for further information about this research?

Researcher Contact Details:

Kyle Barnes, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Auckland 0637, Ph 022 655 4685, kyle.barnes@aut.ac.nz

Project Supervisor Contact Details:

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7056, Andrew.kilding@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 13 September, 2010, AUTEK Reference number 10/160

Participant Information Sheet



Date Information Sheet Produced:

25th May, 2011

Project Title

A Competition-Based Research Design to Assess a Resistance Training Intervention Affecting the Performance and Running Economy of Cross Country Runners

An Invitation

Hi, my name is Kyle Barnes and I am a PhD student at AUT University. In affiliation with Triathlon New Zealand and Athletics New Zealand; along with my supervisors Dr. Andrew Kilding, Dr. Paul Laursen, Dr. Will Hopkins and Dr. Mike McGuigan, I am inviting you to help with a project that is investigating optimal resistance training methods to improve running economy and performance in runners and triathletes.

Before you decide, please read the information below to find out more of what this project is all about. After which, you need to decide whether or not you would like to be involved. You don't have to be involved, and you can stop being involved in the study at any time.

What is the purpose of this research?

Even though we've known about its importance for about 80 years, running economy (RE) has been largely ignored by researchers, coaches and athletes until recently, when we figured out that RE is a better predictor of performance than other more commonly used measures. For example, we regularly measure the maximum volume of oxygen that can be used (i.e. VO_{2max}), but for running events longer than about 5000 m, runners don't use this "maximum" amount, as such events are sub-maximal. Therefore, a more important measure becomes the volume of oxygen that is used when the athlete is running at a sub-maximal speed. Given the importance of RE for endurance performance, successful training interventions that improve RE and ultimately performance would likely be embraced by coaches and athletes. Various resistance training approaches are currently prescribed by coaches and strength & conditioners. However, little information is available pertaining to the optimal type of resistance exercise that maximizes improvements in RE and performance. To this end, the purpose of this research is twofold:

1. Determine the optimal resistance load, using traditional weight lifting methods, to improve RE and performance in well-trained distance runners and triathletes.
2. Determine biomechanical and physiological factors affecting RE in well-trained runners.

How was I chosen for this invitation?

You are part of Hope College's Men's or Women's Cross Country team.

What will happen in this research?

If you decide to participate in this research you will be required to come to the kinesiology lab at Hope College a total of two times for research testing (one before and one after the intervention). The first day of pre-intervention testing will take approximately 90 minutes. You will be asked to participate in a range of laboratory-based physiological and biomechanical assessments. The same time frame should be expected for post-intervention testing.

On the first day anthropometric variables (height, weight, and body composition) will be measured using scales, tape measures and skinfold callipers and BodPod body composition system. Following this you will complete a treadmill test to assess your running economy and VO_2 max. The RE test will involve you running at 5 to 7 submaximal speeds for 4 minutes each with 90 seconds recovery followed by a VO_2 max test which involves you running at the last submaximal speed completed with a progressively increasing gradient until volitional exhaustion. Lastly, you will complete several jumping tests that measure strength and power. Later in the cross country season you will be assessed for maximal lower body strength prior to when the resistance training intervention begins.

During the intervention period will be assigned to one of the two resistance training intervention groups and follow a periodized set of resistance training exercises deemed appropriate by strength and power specialists located at the New Zealand Academy of Sport in Auckland, New Zealand. The intervention period will last 6 to 9 weeks. Additionally, you will be asked to keep a detailed record of your training which will include details such as load, intensity, and volume of training from running and resistance training.

The same tests performed before the intervention will be performed after in the same order.

What are the discomforts and risks?

There are several maximal assessments as part of this research. It is expected that you will experience temporary discomfort during maximal exertion during various run assessments. These tests are used to measure your maximal aerobic capacity and performance capabilities. The amount of exertion at the conclusion of the assessments will be similar to what you will feel at the end of a 5 km or 10 km race. You will be able to interrupt any of the tests if you feel uncomfortable at any time.

How will these discomforts and risks be alleviated?

During the maximal assessments there will be lab attendants present who will be able to assist if you are feeling unwell. A medical facility is located on campus with medical doctors and nurses and other qualified medical staff. Additionally, Kyle Barnes is qualified instructor for the American Red Cross in CPR, First Aid and AED emergency care.

What are the benefits?

You will benefit from this research through having a better understanding of your personal physiological and biomechanical characteristics (VO_2 max, Lactate Threshold, Running Economy, Heart Rate, etc.) as well as (hopefully) becoming more economical through the assigned training intervention group which will ultimately lead to better performances.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the required student insurance provided through your family health insurer or Hope College.

How will my privacy be protected?

All information related to you will be coded in order to ensure that you cannot be identified. The information will remain in locked storage and will only be accessible to the people of the running economy project. No-one will be able to identify you from any of the summary findings for the report of the project. Information regarding your results will only be passed onto others with your permission.

What are the costs of participating in this research?

There are no costs to participating in this research.

What opportunity do I have to consider this invitation?

- You may take the time you need and decide whether or not you would like to be involved.
- You can stop being involved in the project at any point.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to myself.

Will I receive feedback on the results of this research?

Yes, individual feedback will be provided to you, if you request it. The group results will be used in scientific journal articles and conference presentations. Media articles may be written based on the results of the present study.

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

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

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7076, Andrew.kilding@aut.ac.nz

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEK, Madeline Banda, madeline.banda@aut.ac.nz, Ph 921 9999 ext 8044.

Whom do I contact for further information about this research?***Researcher Contact Details:***

Kyle Barnes, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Auckland 0637, Ph 022 655 4685, kyle.barnes@aut.ac.nz

Project Supervisor Contact Details:

Assoc. Prof. Andrew Kilding, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University, Private Bag 92006, Auckland 1020, Ph 921 9999 ext. 7056, Andrew.kilding@aut.ac.nz

Appendix 4: Subject Consent Forms



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

Consent to Participation in Research

Title of Project: **Lower Limb Determinants of Running Economy in Male and Female Runners**
Project Supervisor: **Associate Professor Andrew Kilding**
Researcher: **Kyle Barnes**

- I have read and understood the information provided about this research project (Information Sheet dated 21st June 2010). Yes No
- I have had an opportunity to ask questions and to have them answered. Yes No
- I am not suffering from any injury or illness which may impair my physical performance Yes No
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Yes No
- If I withdraw, I understand that all relevant information will be destroyed. Yes No
- I consent to my data being shared with my coach. Yes No
- I understand that the information collected will be used for academic/feedback purposes only and will not be published in any form outside of this project without my written permission. Yes No
- I wish to have all samples of blood belonging to me, returned to me at the end of each test: Yes No
- I agree to take part in this research. Yes No
- I wish to receive a copy of the report from the research: Yes No

Participant signature:

Participant name:

Date:

Participant's Contact Details:

Phone :..... Email:

Address:

Project Supervisor Contact Details:

Associate Professor Andrew Kilding
Sport Performance Research Institute New Zealand
School of Sport and Recreation
Auckland University of Technology
Private Bag 92006
Auckland 1020
Ph 921 9999 ext. 7056
Andrew.kilding@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee Date 3 August, 2010

Consent to Participation in Research

Title of Project: **Effects of Warm Up with Weighted Vest on Running Economy and Peak Speed**
 Project Supervisor: **Associate Professor Andrew Kilding**
 Researcher: **Kyle Barnes**

- I have read and understood the information provided about this research project (Information Sheet dated 28th February, 2013). Yes No
- I have had an opportunity to ask questions and to have them answered. Yes No
- I am not suffering from any injury or illness which may impair my physical performance Yes No
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Yes No
- If I withdraw, I understand that all relevant information will be destroyed. Yes No
- I understand that the information collected will be used for academic/feedback purposes only and will not be published in any form outside of this project without my written permission. Yes No
- I agree to take part in this research. Yes No
- I wish to receive a copy of the report from the research: Yes No

Participant signature:

Participant name:

Date:

Participant's Contact Details:

Phone :..... Email:

Address:

Project Supervisor Contact Details:

Associate Professor Andrew Kilding
 Sport Performance Research Institute New Zealand
 School of Sport and Recreation
 Auckland University of Technology
 Private Bag 92006
 Auckland 1020
 Ph 921 9999 ext. 7056
Andrew.kilding@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee Date 3 August, 2010



Consent to Participation in Research

Title of Project: **Effects of Different Hill Training Programmes on Running Economy**
 Project Supervisor: **Associate Professor Andrew Kilding**
 Researcher: **Kyle Barnes**

- I have read and understood the information provided about this research project (Information Sheet dated 21st June 2010). Yes No
- I have had an opportunity to ask questions and to have them answered. Yes No
- I am not suffering from any injury or illness which may impair my physical performance Yes No
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Yes No
- If I withdraw, I understand that all relevant information will be destroyed. Yes No
- I consent to my data being shared with my coach. Yes No
- I understand that the information collected will be used for academic/feedback purposes only and will not be published in any form outside of this project without my written permission. Yes No
- I wish to have all samples of blood belonging to me, returned to me at the end of each test: Yes No
- I agree to take part in this research. Yes No
- I wish to receive a copy of the report from the research: Yes No

Participant signature:

Participant name:

Date:

Participant's Contact Details:

Phone : Email:

Address:

Project Supervisor Contact Details:

Associate Professor Andrew Kilding
 Sport Performance Research Institute New Zealand
 School of Sport and Recreation
 Auckland University of Technology
 Private Bag 92006
 Auckland 1020
 Ph 921 9999 ext. 7056
Andrew.kilding@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee Date 3 August, 2010

Consent to Participation in Research

Title of Project: **A Competition-Based Research Design to Assess a Resistance Training Intervention Affecting the Performance and Running Economy of Cross Country Runners**
 Project Supervisor: **Associate Professor Andrew Kilding**
 Researcher: **Kyle Barnes, M.S.**

- I have read and understood the information provided about this research project (Information Sheet dated 25th May, 2011). Yes No
- I have had an opportunity to ask questions and to have them answered. Yes No
- I am not suffering from any injury or illness which may impair my physical performance Yes No
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Yes No
- If I withdraw, I understand that all relevant information will be destroyed. Yes No
- I consent to my data being shared with my coach. Yes No
- I understand that the information collected will be used for academic/feedback purposes only and will not be published in any form outside of this project without my written permission. Yes No
- I wish to have all samples of blood belonging to me, returned to me at the end of each test: Yes No
- I agree to take part in this research. Yes No
- I wish to receive a copy of the report from the research: Yes No

Participant signature:

Participant name:

Date:

Participant's Contact Details:

Phone :.....Email:

Address:

Project Supervisor Contact Details:

Associate Professor Andrew Kilding
 Sport Performance Research Institute New Zealand
 School of Sport and Recreation
 Auckland University of Technology
 Private Bag 92006
 Auckland 1020
 Ph 921 9999 ext. 7056
Andrew.kilding@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee Date 3 August, 2010

Appendix 5: Transfer of Copyright Letters

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The Journal of Strength and Conditioning Research is pleased to consider publication of your manuscript.

In consideration of the publication of the Manuscript, the Author(s) SIGNING BELOW convey(s) all copyright ownership to *The Journal of Strength and Conditioning Research* or its successors including all rights now or hereafter protected by the Copyright Laws of the United States and all foreign countries, all electronic publication rights, well as any renewal, extension or reversion of copyright, now or hereinafter provided, in any country. However, the following rights are reserved for the author(s).

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2. The right to use all or part of this article in future works of their own.

Author warrants that the Manuscript is an original work not published elsewhere in whole or in part except in abstract form, that he has full power to make this grant, and that the Manuscript contains no matter libelous or otherwise unlawful or which invades the right of privacy or which infringes any proprietary right.

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The Author(s) agree(s) not to submit the Manuscript or subsequent revisions for consideration to any other publication unless the Manuscript is rejected by *The Journal of Strength and Conditioning Research*.

Where only one Co-Author signs below, such Author warrants that he is the duly authorized agent of all other Co-Authors.

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AUTHOR indicates acceptance of the above terms of publication by signing and dating this agreement:

_____ Author's Signature	_____ (Print Name CLEARLY)	_____ Date
_____ Author's Signature	_____ (Print Name CLEARLY)	_____ Date
_____ Author's Signature	_____ (Print Name CLEARLY)	_____ Date
_____ Author's Signature	_____ (Print Name CLEARLY)	_____ Date

SECTION B

Exemption for Authors Employed by the United States Government: I attest that the above Manuscript was written as part of the Official duties of the authors as employees of the U.S. Government and that a transfer of copyright cannot be made.

_____ Author's Signature	(Print Name CLEARLY)	_____ Date
_____ Author's Signature	(Print Name CLEARLY)	_____ Date
_____ Author's Signature	(Print Name CLEARLY)	_____ Date
_____ Author's Signature	(Print Name CLEARLY)	_____ Date

SECTION C

Where the Article is a "work made for hire," a duly authorized representative of the Author's employer must SIGN BELOW, indicating acceptance of the above.

AUTHORIZED AGENT SIGNATURE EMPLOYER

DATE

SECTION D

AUTHOR(S) POSTING OF ARTICLES TO AN INSTITUTIONAL REPOSITORY

The *Journal of Strength and Conditioning Research* will permit the author(s) to deposit for display a "post-print" (the final manuscript after peer-review and acceptance for publication but prior to the publisher's copyediting, design, formatting, and other services) 12 months after publication of the final article on his/her personal web site, university's institutional repository or employer's intranet, subject to the following:

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- You may not update the post-print text or replace it with a proof or with the final published version.
- You may not include the post-print or any other version of the article in any commercial site or in any repository owned or operated by any third party. For authors of articles based on research funded by NIH, Wellcome Trust, HHMI, or other funding agency, see below for the services that LWW will provide on your behalf to comply with "Public Access Policy" guidelines.
- You may not display the post-print until twelve months after publication of the final article.
- You must attach the following notice to the post-print: "This is a non-final version of an article published in final form in (provide complete journal citation)".
- You shall provide a link in the post-print to the [name journal]'s website.

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Please disclose below if you have received funding for research on which your article is based from any of the following organizations:

- National Institutes of Health (NIH)

- Wellcome Trust
- Howard Hughes Medical Institute (HHMI)
- Other:
Please List _____

COMPLIANCE WITH NIH AND OTHER RESEARCH FUNDING AGENCY
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A number of research funding agencies now require or request authors to submit the post-print (the article after peer review and acceptance but not the final published article) to a repository that is accessible online by all without charge. Within medical research, three funding agencies in particular have announced such policies:

- The U.S. National Institutes of Health (NIH) requires authors to deposit post-prints based on NIH-funded research in its repository PubMed Central (PMC) within twelve months after publication of the final article in the journal.
- The Howard Hughes Medical Institute (HHMI) requires as a condition of research grants, deposit in PMC, but in its case within six months after publication of the final article.
- The Wellcome Trust requires, as a condition of research grants, deposit in UK PubMed Central within six months after publication of the final article.

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- (a) 12 months following publication of the final article, in the case of NIH,
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Author's Signature	(Print Name CLEARLY)	Date
Author's Signature	(Print Name CLEARLY)	Date
Author's Signature	(Print Name CLEARLY)	Date
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E-mail address:	kyle.barnes@yahoo.com
Journal:	Journal of Science and Medicine in Sport
Our reference:	JSAMS980
PII:	S1440-2440(13)00522-7
DOI:	10.1016/j.jsams.2013.12.005

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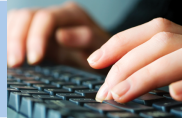
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